SINGLE AND DUAL CONVERTER TOPOLOGIES OF SYNCHRONOUS CONVERTER FOR ELECTRIC TRACTION APPLICATION

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CERTIFICATE

This is certified that the work contained in this thesis entitled "**Single and Dual Converter Topologies of Synchronous Link Converter for Electric Traction Applications**", by S. Srinivasulu (Y110463), has been carried out under our supervision and that this work has not been submitted elsewhere for any degree.

10/4/03

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Abstract

The modern 25 kV ac Traction System favours use of PWM-VSI fed Squirrel Cage induction motor drive due to its numerous advantages. Such system requires an efficient bidirectional front-end converter for converting ac to dc. So far power conversion from ac to dc has been dominated by uncontrolled rectifier or phase-controlled rectifier. Such front-end converter systems suffer from low input power factor at low output voltages and harmonics in input current. These harmonics injected into source can cause faulty operation of signals and interference in telephone lines, and thus results in a number of undesirable effects. Hence, the conventional front-end converters require a reactive power compensator and a passive harmonic filter at the input.

The Synchronous Link Converter can be used as the front-end converter in electric traction due to its unique advantage of high power factor operation and low harmonics in source current. The present work investigates the performance of the Synchronous Link Converter when used as a front-end converter in modern regenerative ac traction motor drive. The unity power factor operation of the Synchronous link converter has been simulated and experimentally verified.

Key words

Synchronous Link Converter, Single and Dual Converter Topologies, Unity Power Factor Operation, Current Harmonics.

Contents

List of Figures

List of Tables

List of Symbols

V_c	Converter Input Voltage
V_d	dc Link Voltage
V_s	Source Voltage
δ	Angle Between Phasors V_{c1} and V_s
I_{s1}	R.M.S Phasor of Fundamental Component of source current
Xs	Synchronous Link Inductor Reactance
V_L	Voltage Drop across Synchronous Link Inductor.
V_{c1}	Fundamental Component of Converter Input Voltage.
Imain	Input current of Main converter in Modified Two Stage Topology
Iauxililary	Input current of Auxiliary converter in Modified Two Stage Topology
Is	Supply Current
Vc1	Input Voltage of First Converter in Two Stage Topology
Vc2	Input Voltage of Second Converter in Two Stage Topology

Chapter 1
Introduction

1.1 Introduction

In the field of electric traction, the ac electrification at commercial frequency began during the year 1955. The overhead catenary supply was fed at 25.0 kV, 50 Hz, single phase supply. Such a system needed power conversion on the Locomotives / Motor coaches for the feeding the dc traction motors.

Initially, the power conversion was done by means of mercury arc rectifier. The maintenance cost of the mercury arc rectifier was very high. In order to overcome this drawback, the semiconductor rectifier system was introduced. Such systems are fed from the overhead catenary supply through a step down transformer. The transformer has a single primary winding and multiple secondary windings, each winding feeding a single phase semiconductor diode bridge rectifier. The primary winding has multiple tappings and an on-load tap changer for varying taps on the transformer without any voltage surges. The diode bridge rectifier feeds the dc traction motors.

Such system has quasi-continuous control of the tractive force/ speed. This affects the utilization of maximum available adhesion. Also with such system the regeneration is not possible, resulting in considerable wastage of power in the dynamic braking resistors, the reduced life and the increased maintenance of brake blocks, wheel tyres, dynamic braking resistors and braking equipments. The presence of tap changer requires frequent maintenance and is susceptible to frequent failures and fire hazards [1].

The multistage phase-controlled converters operating in sequence control and the pulse width modulated converters were used for obtaining the continuous control of

tractive force/speed. These schemes however require a reactive power compensator and a passive harmonic filter at the input, for improving the power factor and to avoid the injection of harmonic currents into the catenary supply [2].

Although these schemes ensured the better utilization of adhesion, the system has drawback due to the use of dc traction motors such as the increased maintenance due to presence of commutator and brush gears, comparatively lower torque compared with the ac traction motors. The ripple in dc link current affected the performance of dc traction motors. Also the regeneration was not economically attractive with these schemes [1].

To overcome these drawbacks, the three phase ac motors has been employed. Such a drive has several important features like regenerative braking capability, very little maintenance and down-time, better utilization of the available adhesion, higher average speed, and higher torque-to-weight ratio, higher operating voltage and higher efficiency.

Both the synchronous motors and the asynchronous induction motors are used in the three phase ac motor traction drives. These motors are fed from either a Voltage Source Inverter (VSI) or a Current Source Inverter (CSI). However modern 25.0 kV, 50 Hz single phase ac electric traction favored the use of VSI-Squirrel Cage induction motor Drives for electric traction application.

Such modern electric traction requires a bidirectional front-end converter. The synchronous link converter which has this capability permits realization of an economic regenerative ac motor traction drive. The use of synchronous link converter as a front-end converter can ensure, nearly sinusoidal input current, and thus reduced harmonic current injection into the overhead catenary supply and near unity power factor operation under

forward and reverse power flow conditions. The low harmonic content in source current can be adequately filtered by a low cost high pass filter [1].

1.2 Objective of Thesis

The objective of the present work is to study the performance of a Single phase Synchronous Link Converter and its unity power factor operation with near sinusoidal current from supply and test it experimentally. Both single and dual converter topologies have been considered. Simulations are done using SABER simulator to investigate Synchronous Link Converter performance when used as front-end converter for 25 kV, 50 Hz, single phase ac regenerative traction drive system in two stage topology. Typical simulation results are validated by experimental results obtained from a prototype fabricated in the laboratory.

1.3 Outline of Thesis

Chapter 2 gives review of the Modern ac Motor Traction Drive, powered from 25.0 kV, 50 Hz, single phase ac supply. The drives fed from the voltage source inverters and the current source inverters and suitability for traction application are covered.

Chapter 3 describes the basic operation of a single phase Synchronous Link Converter. Analysis, simulation and implementation with resistive load have been made. The simulation and experimental results are presented at the end of the chapter.

Chapter 4 presents single converter and dual converter topologies using Synchronous Link Converter for Traction Applications. The simulation results for these two topologies are presented in this chapter.

Chapter 5 gives the overall conclusion of thesis with scope for future work.

Chapter 2

AC Motor Traction Drives

2.1 Introduction

Due to the distinct advantages associated with ac motors, the ac motor drives are gradually replacing dc motor drives in many applications. The modern ac motor traction drives have several important features such as regenerative braking capability, very little maintenance and down-time, near unity power factor operation, nearly sinusoidal current, good adhesion, higher average speed, and higher efficiency.

2.2 Important Features of an Electric traction Drive

The following are some of the important features of an electric traction drive system [1].

1. For economic reasons, the 25 kV, 50 Hz ac traction employs only single phase supply although the rating of locomotive is as high as 6000 hp.
2. The traction supply is weak in nature and hence the voltage is subjected to fluctuations and may vary from 19 to 27.5 kV on continuous basis. The supply has sharp voltage fluctuations, including discontinuity when the locomotive crosses from one supply section to another.
3. As the traction supply is weak in nature, the reactive power has very adverse effect. It is essential that the power factor is not allowed to be lower than 0.8.
4. The use of electric braking reduces wear and tear on the track, wheels and brake shoes, thereby increasing their life substantially.

5. The dynamic braking is generally used. But when the energy saving is sufficiently large to justify additional cost of the drive, the regenerative braking is preferred.
6. The regenerative braking is generally combined with the dynamic braking.
7. The use of controlled rectifier results in the generation of harmonics, which are injected into the source. This results in the following adverse effects :
   a) The high frequency harmonics cause the interference with communication line.
   b) The low frequency harmonics may enter into the track circuits, leading to mal operation of the signals.
   c) They cause sharp fluctuations in the supply voltage.

2.3 Advantages of ac Motor Traction Drives Over the dc Motor Traction Drives

The modern traction drives generally use three phase induction motors as traction motor. The ac motor drive has following advantages:

1. Three phase induction motors are robust and have high torque-to-weight ratio.
2. Simplified and reduced maintenance because of the absence of commutator and brush gear as in dc motor drives.
3. The full use of available adhesion between the wheel and the rail, because of the naturally steep torque – speed characteristics of induction motor.
4. The induction motor has a good regeneration capability.
5. Due to absence of the commutator, the motor windings can be designed for higher voltages. This results in more favorable design of the other components such as inverter, converter, transformer secondary, etc.

6. At the same power level, induction motor is lighter than dc motor. This results in relatively smaller mass of the truck giving a good riding characteristic and results in a low rail stress.
7. The three phase induction motor has improved efficiency and reliability in operation than dc motor.
8. With three phase drive, the electric braking down to standstill is possible.

2.4 Suitability of VSI and CSI Drive for Traction Application

The three phase ac induction motor should be fed from a three phase supply capable of delivering step less variable frequency and voltage. The current source inverter (CSI) and the voltage source inverter (VSI) are available to meet this requirement. The important relative merits and demerits of CSI and VSI drives in relation to traction are as follows [1] [3]:

1. CSI drives do not suffer from the shoot through fault which is major drawback in VSI drives.
2. The regenerative braking capability is inherent in a CSI drives fed from a line commutated fully controlled converter or a PWM fully controlled converter and in VSI drive powered from a Synchronous Link Converter. If the ac supply fails the regenerative braking will not be possible in both the drives. Under such conditions, a VSI drive can use dynamic braking but the same is not possible with CSI drive.
3. The presence of large value inductance in the dc link of a CSI drive results in slower dynamic response compared to PWM-VSI drive. Consequently VSI drive has better adhesion (i.e. the lower possibility of wheel slip).

4. When the source is dc a PWM-VSI drive will be cheaper compared to a CSI drive of the same rating. Also the requirements of the large commutation capacitors and a large dc link inductor, which is oversized to prevent saturation, lead to higher volume and weight of CSI drive compared to PWM-VSI drive.
5. The frequency range of CSI is lower than VSI drive. Hence the CSI drive has a lower speed range.
6. The CSI is not suitable for multi-motor drives. Hence each motor is fed by its own inverter and rectifier. But a single diode bridge or a Synchronous Link Converter can be used to feed a number of VSI motor system. Alternatively, a single VSI can feed a number of motors.

2.5 AC Motor Traction Drive

2.5.1 Principle of operation

The block diagram of a popular ac motor traction drive is shown is Fig 2.1.The pantograph collects the power for the running locomotive from the overhead line. The pantograph is connected to the primary of transformer. The isolation and protection devices are provided between the pantograph and the transformer.

The traction transformer has a single primary winding and multiple secondary winding for feeding the traction converters. The traction transformer is so designed that the percentage impedance of all the secondary windings feeding traction converters are maintained unchanged irrespective of the combined or isolated operation of windings.

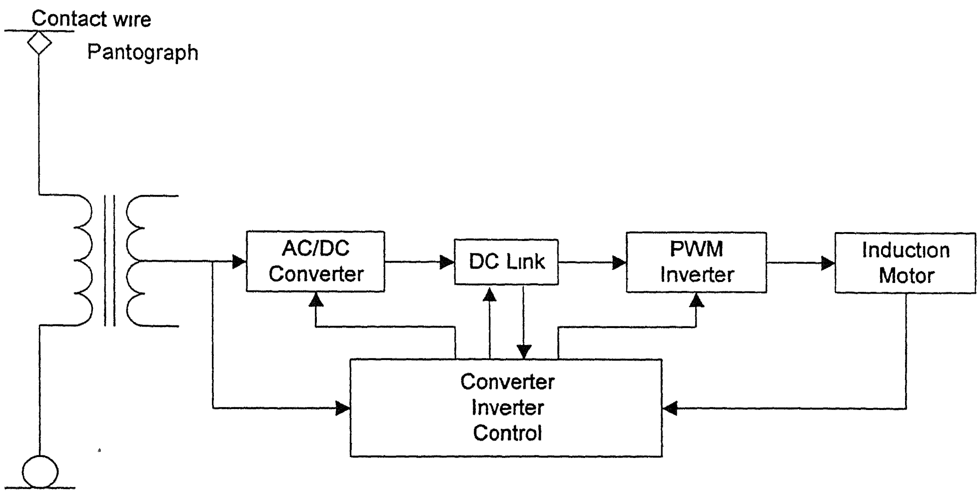


Fig. 2.1 A Popular ac Motor Traction Drive System

The traction power converters consist of PWM converters. These are connected in series or parallel. Each unit is of modular construction with the built-in cooling arrangements. The converters are controlled in a way as to maintain unity power factor, throughout the operating range, with practically zero harmonic injection into the line.

The dc link consists of a suitable bank of capacitors designed to provide a stable dc link voltage for feeding variable voltage and variable frequency inverter (VVVF) in voltage source configuration. Alternatively, dc link may consist of a suitable inductor designed to provide a stable dc link current for feeding CSI inverter in current source configuration.

The dc link decouples the drive from the source. The inverter used may be CSI type or VSI type. Generally CSI is used with synchronous motors drives and VSI is used with induction motor drives. The output of the inverter is connected to three phase traction motors. The synchronous motors have higher full load efficiency and power factor than induction motors. However, compared with the induction motors, synchronous motors have higher cost, weight and volume for the same rating and require more maintenance.

Generally microprocessor based control systems are used for the converter control, dc link control, inverter control, traction motor control, braking control and slip control. The microprocessor also performs the task of fault diagnostic and display in addition to the control task.

2.5.2 Control of three phase ac motor traction drives

Several drives employing the squirrel cage induction motors and the synchronous motors are in use for traction. Variable frequency control is used both for the induction motors and the synchronous motors.

The modes of operation of the induction traction drive are shown in Fig 2.2. This drive has received wide acceptance.

When the drive is in the motoring region, the characteristics curve has the following three regions [1]:

1. Constant Torque region
2. Constant Power region.
3. Slip limited region.

1. Constant torque region:

The constant torque region lies from the standstill to base speed (ω_b). In this region the inverter is operated to supply adjustable voltage and frequency to the motor. The motor voltage is adjusted as speed (frequency) changes to maintain a constant flux density in the motor. The motor voltage therefore increases proportionally with the speed (frequency). The frequency of voltage induced in the rotor (slip frequency) is held constant. This produces nearly constant torque since the power output is proportional to the speed, the

power increases linearly with speed. At base speed (ω_b), the ac voltage reaches the maximum limit of inverter.

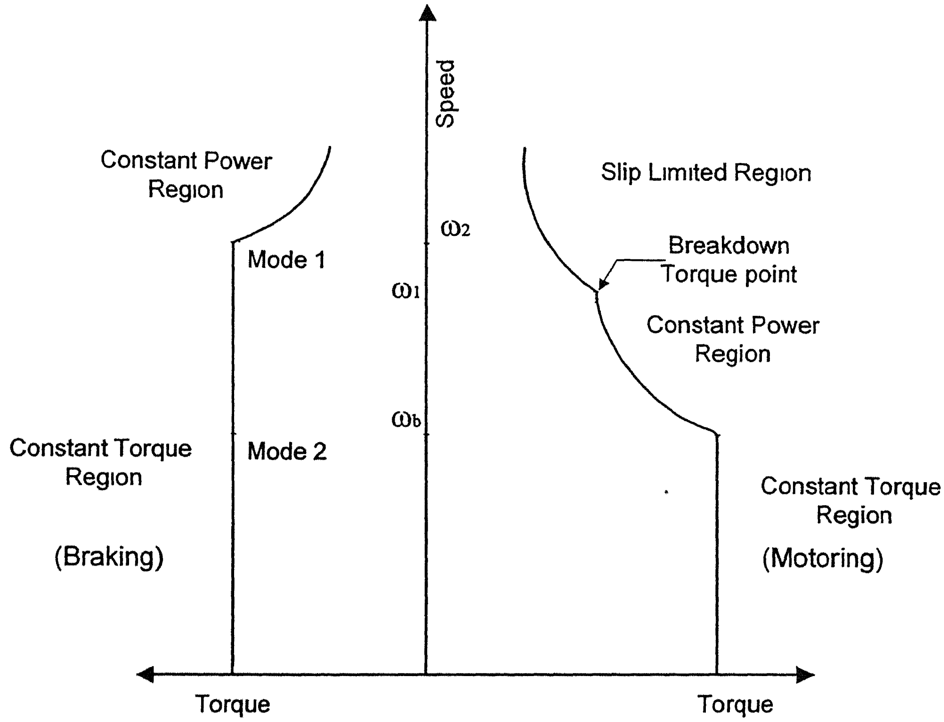


Fig. 2.2 Modes of operation of ac Motors with VVVF control

2. Constant power region:

In this region, the inverter is operated to supply the adjustable frequency to the motor while the voltage is no longer adjustable and the inverter is operated at the maximum voltage limit. The power output from the motor remains nearly constant. This mode of control is extended until point (ω_1), where the motor breakdown torque limit is reached. Any attempt to operate the motor at the maximum permissible current beyond this speed will stall the motor.

3. Slip limited region:

In this region, the slip frequency is maintained constant and any increase in the speed is done by reducing the motor current. Here the motor current reduces inversely with the

speed and the torque decreases inversely as speed squared. This characteristic is often referred to as series motor characteristic. The torque produced in this region is some what higher than that produced by a dc series motor.

When the drive is in braking region, the characteristic curve has the following regions of operation [1]:

1. Constant power region.
2. Constant torque region.

1. Constant power region:

In this region, the drive power is held constant to match the inverter maximum power capability. This mode is similar to constant power mode during motoring and slip frequency varies proportional to the speed.

2. Constant torque region

When the drive is braking, the constant torque region has two modes of operation.

Mode1: In this region, both the motor voltage and current are varied approximately as square root of speed. Hence the power varies directly with speed, as the slip frequency is varied in direct proportion to the speed. The power fed back to the source is proportional to the speed, decreasingly linearly with speed.

Mode2: In this region, the motor current is held constant as slip frequency is held constant. The motor voltage therefore reduces proportionally with the speed (frequency). At low speeds the electric braking is gradually withdrawn.

2.5.3 Requirement of ac Motor Traction Drive

1. The source side converter shall ensure a power factor as nearly unity as possible.

2. The converter shall be designed in a way to keep psophometric disturbance current with in the enforced limit.
3. The converter shall be designed in such a way, as to cause no interference to track circuit, signal and telecommunication equipments.
4. The power converter/inverter shall ensure a four quadrant operation and regenerative braking shall be available from maximum speed range up to standstill.
5. The power converter/inverter shall ensure the full utilization of the available adhesion.
6. The inverter shall incorporate beat less control system to suppress beat phenomenon.

2.6 VSI–Squirrel Cage Induction Motor Drive

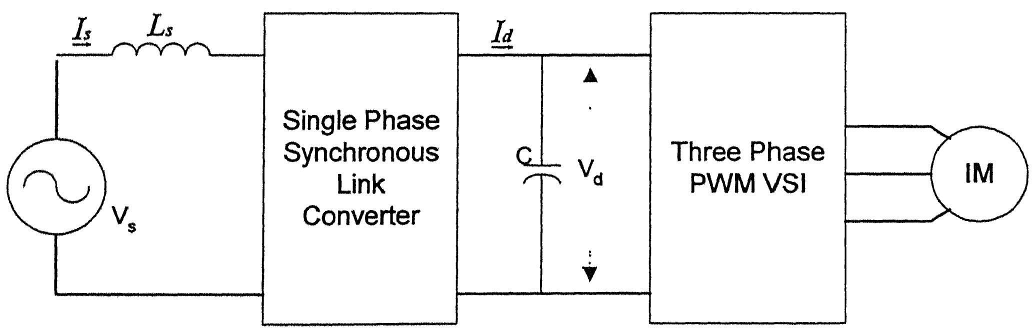


Fig. 2.3 Regenerative Induction Motor Drive using Synchronous Link Converter

A regenerative induction motor drive using a Synchronous Link Converter is shown in Fig 2.3. The Synchronous Link Converter permits realization of an economic regenerative ac drive with nearly unity power factor and a low harmonic content in the

source current by proper operation of converter with pulse width modulation. The converter circuit is shown in Fig 3.1

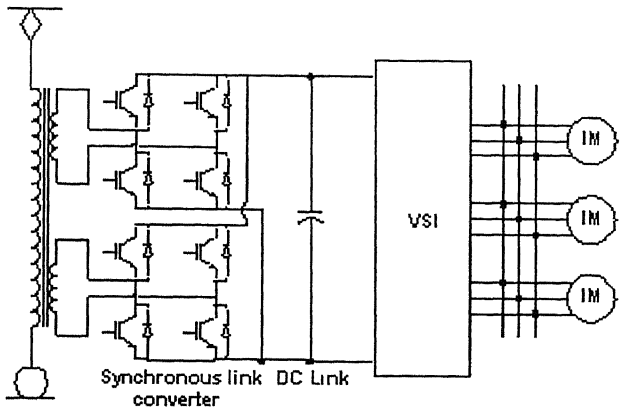


Fig. 2.4 Three Phase Regenerative Traction Drive

Fig 2.4 shows three phase regenerative traction drive using Synchronous Link Converter, and PWM inverter. Here two Synchronous Link Converters are connected in parallel feeding an inverter, which in turn feeds three induction motors connected in parallel. Depending upon the power levels IGBT / GTO can be used in the construction of Synchronous Link Converter. In the case of Motor coaches, IGBT's can be used both in Synchronous Link Converter and inverter. As they can be operated at higher switching frequency, the harmonics in source current can be reduced to a smaller value. We can use sinusoidal PWM, current controlled PWM or vector PWM for both converters and inverter. For high power levels GTO thyristors are operated at lower frequencies, generally sinusoidal PWM is used and more than one converter is operated in parallel to keep the harmonics in the source current within acceptable limits.

The modern VSI squirrel cage induction motor traction drives are generally torque controlled drives. The drive is started with reduced voltage and frequency. This frequency reduction improves the motor power factor and increases the torque per ampere at the start. Hence the rated torque is available at the start, and the drive is

accelerated to its operating speed. The drive is operated in a way described in section 2.5.2. Here the power transfer is from source to the load.

For transferring the operation from the motoring to regenerative braking, the inverter frequency is reduced. A reduction of the inverter frequency makes the synchronous speed less than the motor speed and transfers operation from quadrant I to quadrant II. Here the power flows from motor to dc link and from dc link to the source. The inverter voltage and the frequency is reduced to brake the machine to zero speed.

For speed reversal, the phase sequence of inverter voltage is reversed by interchanging the control signals between the switches of any two legs of inverter. In the scheme described above, when the source is unable to take back the regenerated power, the dynamic braking scheme can be used. For this purpose a braking resistor is provided in series with switch across the dc link capacitor. The generated power charges the filter capacitor and its voltage rises. When the voltage reaches a prescribed maximum limit, the switch is turned on, connecting the braking resistor across the capacitor. The energy generated and the energy supplied by the filter capacitor is dissipated in the braking resistor. When the capacitor voltage reaches the prescribed minimum limit the switch is turned off. Again the capacitor voltage starts rising and the cycle repeats. Thus only that portion of the regenerated energy is dissipated by dynamic braking resistor which cannot be accepted by the source.

Generally, the indirect current control technique is used with Synchronous Link Converters for ac motor traction drive. In this control technique, for a given value of reference, the power input to the converter has a fixed value. When the load on the converter is decreased, then there would be unbalance between power input and the

power output. Hence a closed loop control is provided across the Synchronous Link Converter.

2.7 Harmonic Reduction and Control of Torque Pulsation

The line side converter generates current harmonics which are injected into the overhead lines. Hence the measures are to be taken to keep the harmonics below a desired limit. Some of the methods used with VSI Squirrel cage induction motor drives are

1. By series / parallel connection of converters the supply current harmonics can be reduced considerably. If 'n' converters are put in series / parallel and if the carrier signals of the individual converters are equally displaced within one half of carrier period interval by an angle π/n radians, then some of the reflected harmonics cancel on the primary side of transformer. The ripple frequency of the primary current has a frequency (n x f_c), where 'n' is the number of converters put in parallel/series and f_c is the carrier signal frequency [4]. For example if the Synchronous Link Converter is realized by using two IGBT converters, say converter I and converter II in parallel, then the firing of the IGBT's in converter I and converter II can be done by using a common modulating signal and the triangular carrier wave phase shifted from each by an angle 90 deg (because n=2) as shown in fig 2.5.
2. By using three level converter as compared to two level converter [2] [3].
3. By employing switched electronic compensator which generates an exact replica of the harmonic currents. It is fed into traction transformer to produce harmonic counter emf. This ensures that the transformer main flux is sinusoidal, and hence

the induced voltage in the primary. The line current is low pass filtered by the transformer leakage inductance and assumes a sinusoidal waveform [5].

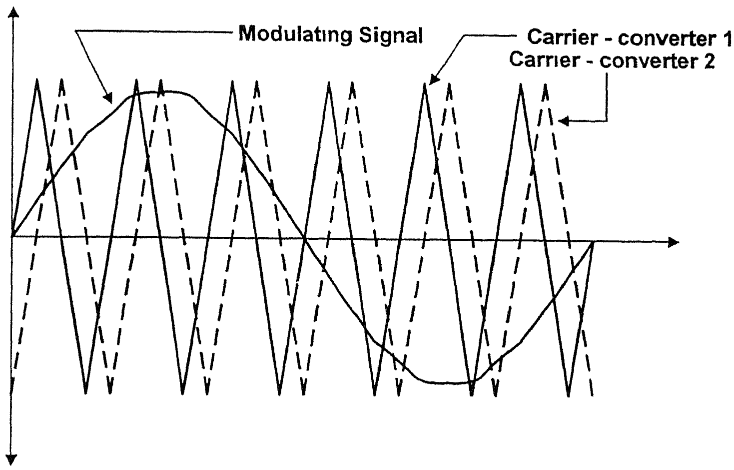


Fig. 2.5 Carrier waves for two converters operating in parallel

For reducing the harmonics in the inverter output voltage and to minimize torque pulsations, the inverters can be connected in parallel. They share the common dc link voltage and ac output terminals of the respective phases are connected through an inter phase reactor. The midpoint of the inter phase reactor is connected to the respective phases of an induction motor. The inverters operated with common modulating signals, but the carrier signals of individual inverters being equally displaced within carrier period interval. Also when the traction drive is in constant torque region, the inverter is operated in asynchronous mode to limit the torque pulsation [5].

2.8 Advantages of VSI Squirrel Cage Induction Motor Traction Drive

The VSI squirrel cage induction motor traction drive has the following advantages [1]:

1. Unity input power factor.
2. Low harmonic content in the source current.
3. Regenerative braking capability at low cost.
4. Smooth acceleration due to absence of low speed torque pulsation.

5. Efficient and quiet operation due to low harmonic content in the motor input voltage.
6. Good adhesion due to fast dynamic response and absence of torque pulsations.
7. Multi motor drive possible due to VSI.
8. Regenerative braking capability offers energy saving.
9. The dynamic braking can be resorted in the event of catenary failure due to use of VSI.
10. Improved energy efficiency.
11. Reduced maintenance cost.
12. Reduction in the size and weight of the traction circuit equipments.

2.9 Conclusion

The ac motor traction drives are superior to dc motor traction drives. The recent advances in Power Electronics, in drive control techniques and availability of microcontrollers for control and fault diagnosis has enabled the realization of the traction drive with high efficiency, high level of performance and low down time. The numerous advantages of VSI Squirrel Cage Induction Motor Drive allow it to be the best suited ac traction drive.

Chapter 3

Synchronous Link Converter and its Experimental Verification

3.1 Introduction

The power conversion from ac to dc has so far been dominated by uncontrolled rectifiers or line commutated, phase controlled rectifiers. Such converters have the inherent drawbacks such as harmonics in input current and output voltage; low input power factor especially at low output voltages. Several applications require front-end ac to dc converters, having both rectifying and regenerating abilities. Dual converters are used under such circumstances, but they have complicated control and power circuits. The Synchronous link converter is the best solution and can be used as front-end converter for the applications requiring both rectification and regeneration capabilities.

The advantage of synchronous link converter (SLC) is that it can be operated at any desired power factor taking near sinusoidal input current. This chapter deals with the design, simulation and experimental verification of a single-phase synchronous link converter with a resistive load. The electric traction uses single phase supply even at high power level. Also for many low power ac/dc drives, UPS system operates from single phase supply. These low / high power drive systems at present require synchronous link converter as front-end converter.

3.2 Principle of Synchronous Link Converter

Fig. 3.1 shows the circuit of a single-phase synchronous link converter. The switches S_1, S_2, S_3 and S_4 are self-commutating switches. This circuit resembles a voltage source inverter. When the switches are operated with a known pulse width modulation technique, the converter produces a voltage V_c at the converter-input terminals. If the dc link voltage V_d is maintained constant, the magnitude of V_c can be varied by adjusting the modulation index of the converter. The phase of the converter input voltage V_c with reference to supply voltage V_s can be altered by changing the phase of switching pulses with respect to V_s [6].

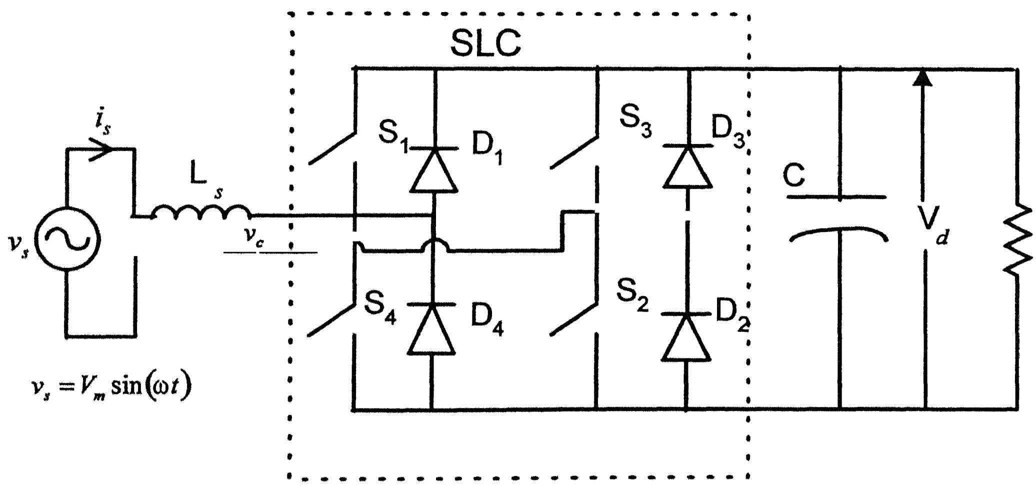


Fig. 3.1 Single Phase Synchronous Link Converter

Let I_{s1} be the rms phasor fundamental component of source current and V_{c1} is the rms fundamental component of V_c, under Unity Power Factor (UPF) condition. Assuming the source voltage, V_s to be sinusoidal without any harmonics, the phasor diagrams for rectification and inversion modes taking $\overrightarrow{Vs}$ as the reference phasor are given in Fig. 3.2

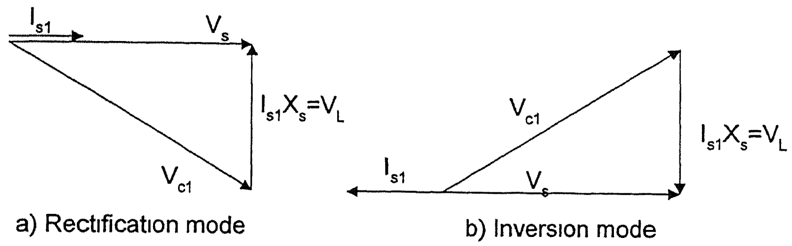


Fig. 3.2 Phasor diagrams of Synchronous Link Converter

$$\overrightarrow{V_s} = \overrightarrow{V_{c1}} + \overrightarrow{V_L} \tag{3.1}$$

$$\overrightarrow{V_L} = j\omega L_s \overrightarrow{I_{s1}} \tag{3.2}$$

The magnitude and phase of the fundamental converter voltage V_{c1} are given by,

$$V_{c1} = \sqrt{V_s^2 + V_L^2}$$
$$\delta = \tan^{-1}\left(\frac{V_L}{V_s}\right) \tag{3.3}$$

where δ is angle between phasors V_{c1} and V_s.

Real power transferred from the source to the converter, $P = V_s I_{s1}$

From the phasor diagram, Fig.3.2

$$I_{s1}X_s = V_L = V_{c1}\sin\delta \tag{3.4}$$

$$V_s = V_{c1}\cos\delta \tag{3.5}$$

$$P = \frac{V_s V_{c1}\sin\delta}{X_s} \tag{3.6}$$

From above equations, it can be seen that for a given supply voltage V_s and a chosen value of L_s, the desired magnitude and phase of the converter input voltage V_{c1} can be obtained for UPF operation.

The phasor diagrams for UPF operation under forward and reverse power flows are shown in Fig. 3.2 resembles the vector diagrams of a synchronous machine supplying

and regenerating from an active load. The supply inductance L_s separates the supply voltage, V_s and the converter input voltage V_c and thus works as a synchronous Link.

Synchronous link converter works in boost mode. The output dc voltage is fixed and is higher than the peak of the supply voltage. Thus a fixed ac input voltage is converted into a fixed output dc voltage. The output power is controlled by controlling the dc link current. Due to the operation of synchronous link converter with PWM switching pattern it has a sinusoidal input current and a high quality dc output voltage. These features result in the smaller size of input and output filters and hence result in high efficiency.

In SLC, it is required to regulate the dc link voltage for matching the input power to the converter with the power demand from the dc link. A closed-loop dc link voltage control is employed to keep the dc link voltage constant. The converter is operated at UPF for either direction of power flow.

3.3 Control Technique for a Synchronous Link Converter

For proper operation of Synchronous Link Converter it should be operated in closed-loop mode. The converter uses the following current control technique [7].

1. Hysteresis current control.
2. Predictive current control with fixed switching frequency.
3. Indirect current control.
4. Load current control.

In the case of Electric Traction, where the power involved is very high and also more than one converter are connected in parallel in order to keep the harmonics within acceptable limits and they are operated with indirect current control.

3.3.1 Indirect current control

In the case of Synchronous Link Converter it is required to regulate the dc link voltage by matching the input power to converter with the power demand from the dc link [6]. This power balance is to be maintained at unity power factor for either direction of power flow.

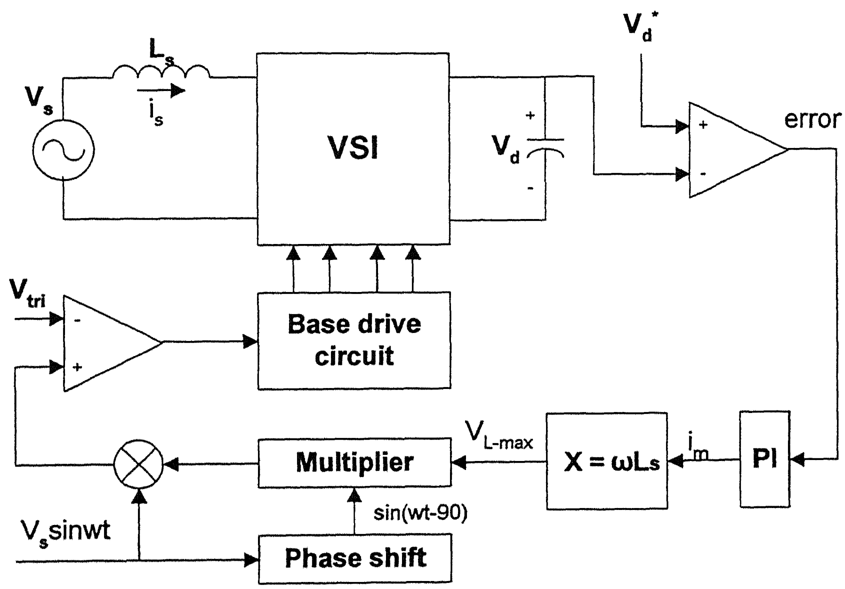


Fig. 3.3 Indirect current control of Synchronous Link Converter

In the case of indirect current control scheme, the ac input current is indirectly controlled by the standard sinusoidal PWM, which essentially modulates the fundamental component of converter input voltage V_c. The equations governing the current control, neglecting resistance of the synchronous link inductor and source are (3.1) and (3.2).

The schematic diagram of such a scheme is shown in Fig. 3.3. The error in dc link voltage V_d from the set reference V_d^* defines the input current required which when processed through a PI controller gives the peak value of current. It is then multiplied with reactance (synchronous link inductor) and phase shifted sine wave and added with

source voltage to get the modulating signal displaced at δ degrees. This modulating signal controls the fundamental component of the converter-input voltage and current at unity power factor.

The main advantage of this control is that the harmonics at the converter input voltage and in converter input current occur at the well-defined frequencies. Therefore, filters can be designed to suppress those harmonics. However, this method of control is sensitive to the changes in values of supply parameters and is slow in response [7].

3.4 Design of Synchronous link converter

For the proper operation of Synchronous Link Converter the following factors have to be considered:

3.4.1 Loss of Control Limit

The anti-parallel diodes have to be normally reverse biased. This condition ensures that switching of the devices can control the waveform of ac input current. This requires that the dc link voltage V_d to be always greater than the peak of ac voltage [7].

$$V_d \geq \sqrt{2} \cdot V_s \tag{3.7}$$

3.4.2 Maximum Operating Range

The Synchronous Link Converter has the constant output voltage and the output voltage is independent of the input voltage. Also the output voltage is higher than the peak of supply voltage, so that the anti-parallel diodes across the switches are all reverse biased. Hence for the proper operation of synchronous link converter, there is a restriction on the output voltage given by following equations.

For unity power factor operation we have

$$V_{c1} = \sqrt{V_s^2 + (I_{s1} X_s)^2} \tag{3.8}$$

$$V_{c1} = \frac{M_f V_d}{\sqrt{2}} \tag{3.9}$$

for pulse width modulation with unipolar switching.

Substituting (3.9) in (3.8) and solving for I_{s1} for M_f=1 we get

$$I_{s1b} = \sqrt{\frac{0.5 V_d^2 - V_s^2}{X_s}} \tag{3.10}$$

Where I_{s1b} is the maximum permissible rms input current (also known as current distortion limit) for given value of dc link voltage V_d, supply voltage V_s and synchronous link inductor L_s.

It is evident that the operating region of a Synchronous Link Converter is higher with lower value of Synchronous link inductor and higher value of dc link voltage.

3.4.3 Selection of dc link voltage

Generally the Synchronous Link Converter is used as front-end converter in the ac regenerative variable speed drives. Hence the dc link voltage is decided by the line to line voltage rating of the motor.

3.4.4 Selection of synchronous link inductor

For the deciding the value of Synchronous Link inductor, the following factors are to be considered.

For proper operation of the Synchronous Link Converter, it is essential that the maximum modulation index at which the converter operates is close to unity, as permitted by the turn off time of devices used. Under such conditions, the magnitude of converter input voltage V_{c1} varies over wide range, with the change in power demand on

the converter. This will ensure that the control will be less sensitive to errors. Assuming that the converter operates with unity power factor, we can obtain expression for the modulation index as given by the following equation

$$M_f = \frac{\sqrt{V_s^2 + (I_{s1}X_s)^2}}{\frac{V_d}{\sqrt{2}}} \tag{3.11}$$

Equation (3.11) suggests that if a very low value of inductor is used, the range of variation of modulation index (M_f) and hence converter input voltage V_{c1} becomes very much limited (with the change in load on the converter) and hence control becomes sensitive to errors. For maximum allowable modulation index, the maximum limiting value of the inductor can be obtained as follows:

From the Fig 3.2 we have

$$V_s = V_{c1} \cos \delta \tag{3.12}$$

$$I_{s1} = \frac{V_s - V_{c1}}{X_s} \tag{3.13}$$

$$P_{in} = \frac{V_s V_{c1} \sin \delta}{X_s} \tag{3.14}$$

$$P_{out} = V_d I_d \tag{3.15}$$

For loss less converter we have, $P_{in} = P_{out}$

$$\frac{V_s V_{c1} \sin \delta}{X_s} = V_d I_d \tag{3.16}$$

From (3.16) solving for L_s we get,

$$L_s = \frac{V_{c1} V_s \sin \delta}{\omega V_d I_d} \tag{3.17}$$

For a given dc link voltage the maximum input voltage is given by

$$V_{c1\max} = \frac{M_{f\max} V_d}{\sqrt{2}} \tag{3.18}$$

Where, $M_{f\max}$ = the maximum modulation index as decided by turn off time of the devices used.

$$\delta_{\max} = \cos^{-1}\left(\frac{V_s}{V_{c1\max}}\right) \tag{3.19}$$

Substituting the (3.19) in (3.17) we get

$$L_{\max} = \frac{V_s V_{c1} \sin \delta_{\max}}{\omega V_d I_{d\max}} \tag{3.20}$$

Where $I_{d\max}$ = maximum value of the dc link current.

The dominant harmonics in the input voltage of the converter will occur around the frequency $2f_c$ where f_c is the switching frequency [8]. The inductor should be designed to keep the ripple in the input current at this frequency around certain percent of the maximum input current. The actual I_{rms} can be considered to be 1.05 times the calculated I_{rms} to account for harmonic currents, power losses etc. Also since the synchronous link inductor is on ac side the ripple current is low, the inductor can be designed with iron core. However increase in core loss due to high frequency ripple current must be taken into account.

3.4.5 Selection of Output Filter Capacitor

The main criterion for selecting dc link capacitor C_d is based on the allowable ripple in dc link voltage. It is usual to limit the ripple voltage due to second harmonic currents within 5% of the rated value of dc link voltage. As the output of the dc link is fed to an inverter, effective measures have to be taken to limit the effect of the second

harmonic component. Generally tuned filters are used to attenuate the second harmonic current in the dc link. To restrict the capacitor ripple voltage to x% of the dc link voltage V_d, the value of the capacitor should be

$$C_d \geq \frac{V_s I_{s1} \cdot 100}{2\omega V_d^2 x} \tag{3.21}$$

The rms current through the capacitor is given by

$$I_{crms} = \frac{I_d}{\sqrt{2}} = \frac{V_s I_{s1}}{V_d \sqrt{2}} \tag{3.22}$$

Hence the rms current rating of the capacitor has to be greater than I_{crms} as given by the (3.22). The dc voltage rating of capacitor will depend upon the dc link voltage. It is necessary to have a safety factor of 1.25 for actual rated voltage of capacitor, over actual dc link voltage to account for over charging during transients.

3.4.6 Device rating

(a) Forward Blocking voltage – The forward blocking voltage of the GTO / IGBT will be chosen by following condition – when any of the switches conduct, the switch in same leg has to block the full dc link voltage V_d. Hence the forward blocking voltage rating of the switch should be greater than the dc link voltage V_d. Generally a margin of about 25% is to be given, after taking into consideration the dc link voltage and the voltage jump on account of inductance and capacitance in the circuit.

(b) Forward dv/dt – Maximum forward dv/dt occurs at every turn on. In order to protect the device against high dv/dt, generally a snubber circuit is connected across the devices.

3.5 Digital Simulation

Digital simulations of single phase synchronous link converter, with a resistive load across the dc link capacitor are done. The converter circuitry has been divided into three circuits namely; Power circuit (Fig. 3.4), Control circuit (Fig. 3.5) and Gate drive circuit (Fig. 3.6) and are simulated with SABER simulator. The power circuit consists of the semiconductor switches, source supply and load with dc link capacitor. The control circuit consists of error detection of dc link voltage with a fixed reference voltage, PI controller and circuitry for calculating the modulating wave. The gate circuitry generates switching signals for the converter with modulating signal obtained in control circuit.

The voltage source and semiconductor switches used in simulation are ideal. The simulations were made at different switching frequencies to study its effect on harmonics of source current. The parameters used in the simulation are given below.

Supply Voltage	50 V rms, 1-Φ, 50 Hz
Dc-link Voltage	100 V
Synchronous Link Inductor	22.72 mH
Output filter capacitor	2200 μF
Load	50 W, 200 Ω

The simulation results are presented along with experimental results in the next section.

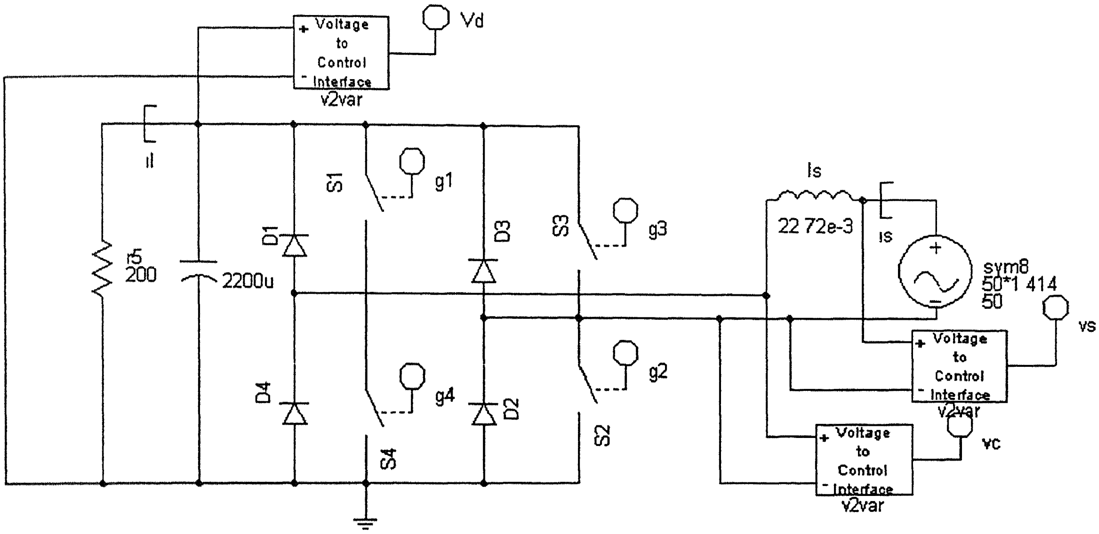


Fig. 3.4 Power circuit used in simulation

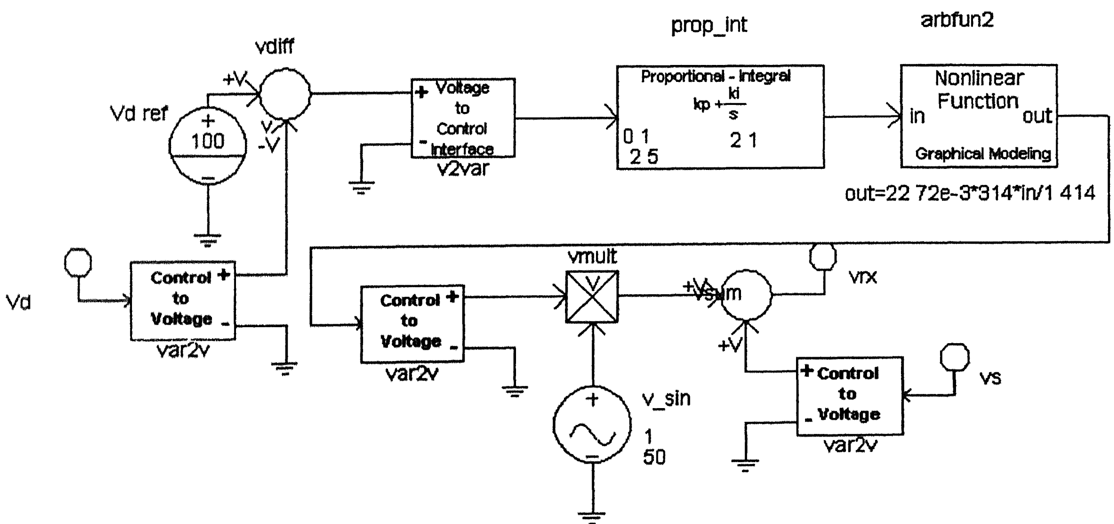


Fig. 3.5 Control circuit used in simulation

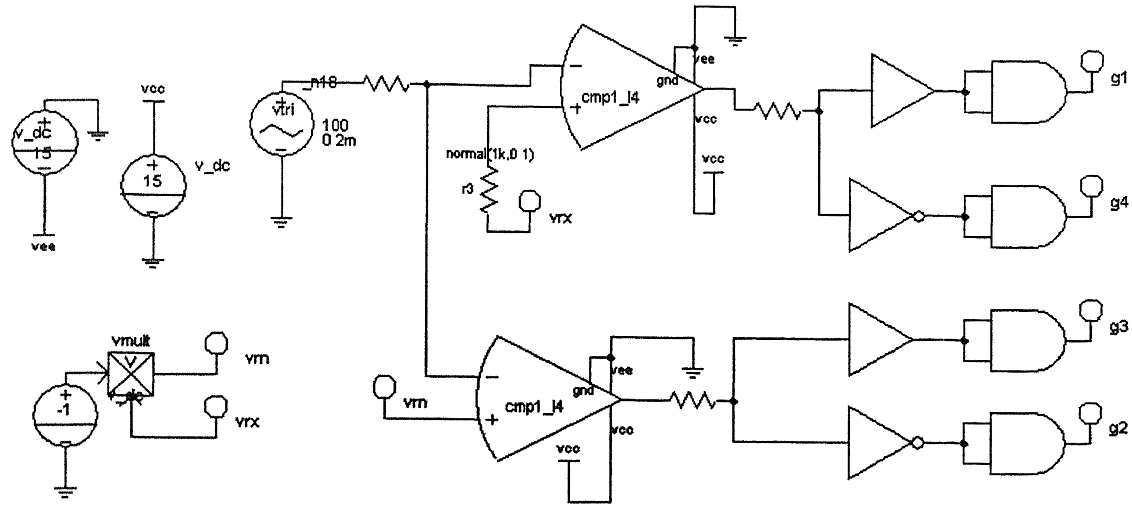


Fig. 3.6 Gate circuit used in simulation

3.6 Experimental Verification and Observation

3.6.1 Objective

The experimental verification was made to study the unity power factor operation of Synchronous Link Converter. The converter was operated at different switching frequencies to study the current harmonics in source current. The experimental unit of the converter was designed with the specifications used in digital simulation.

3.6.2 Power circuit

The power circuit of the Converter was realized using IGBT switches. The synchronous link converter was fed through a variac. The following components are used in the power circuit.

1. MITSUBISHI CM75DU – 24F IGBT dual power module; 75 A, 1200 V.
2. 0.1 μF, 36.0 Ω Snubber
3. 22.72 mH Synchronous Link Inductor and 2200 μF output filter capacitor.
4. 50 W load.

3.6.3 Control circuit

The control circuit (Fig 3.7) is partially realized with analog hardware and partially with computer interface. A high performance data acquisition card, PCL-208, whose details are given in Appendix-B has been used to interface the PC with the external hardware. The dc-link voltage is sensed using a Hall sensor and fed to the computer through the data acquisition card. Using a computer program, the dc link voltage is sensed by data acquisition card, and the error in dc-link voltage is processed by PI controller. It is then multiplied with the reactance of synchronous link inductor and sent to the external hardware through D/A channel PCL-208. The signal is then filtered and multiplied with phase shifted sine wave using analog multiplier ICL8013 and added with source voltage signal to get the modulating waveform.

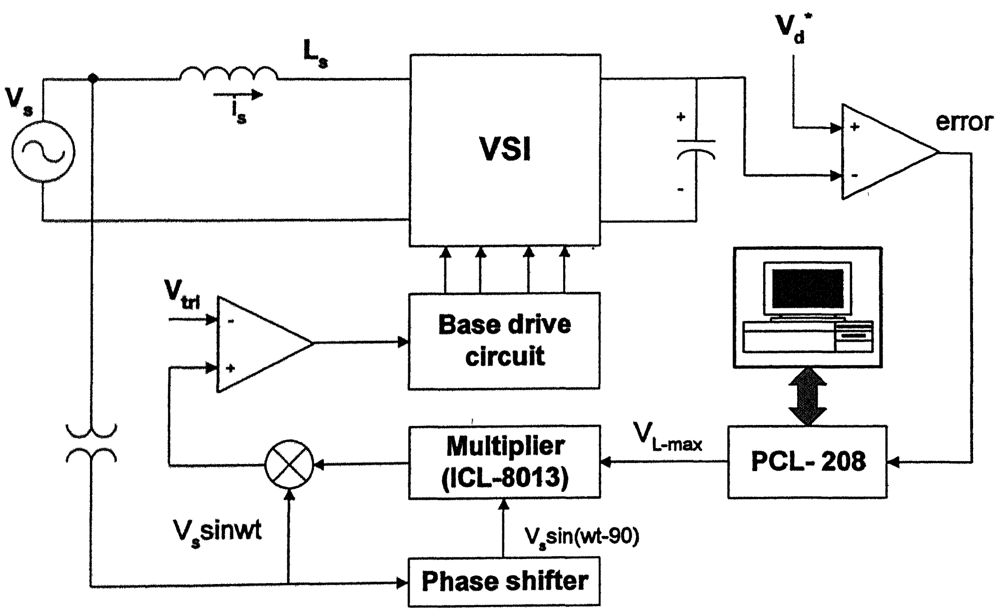


Fig. 3.7 Control circuit used in experiment

3.6.4 Base drive circuit

Fig 3.7 gives the circuit connections of base driver circuit. The function of driver circuit is to provide electrical isolation between the control circuit and power circuit. The electrical isolation is achieved through optocoupler 6N137. The driver circuit also amplifies the low – level switching signal coming from the control to circuit to the level sufficient to drive the IGBT. Further the driver circuit provides over current protection by cutting signals during abnormal conditions.

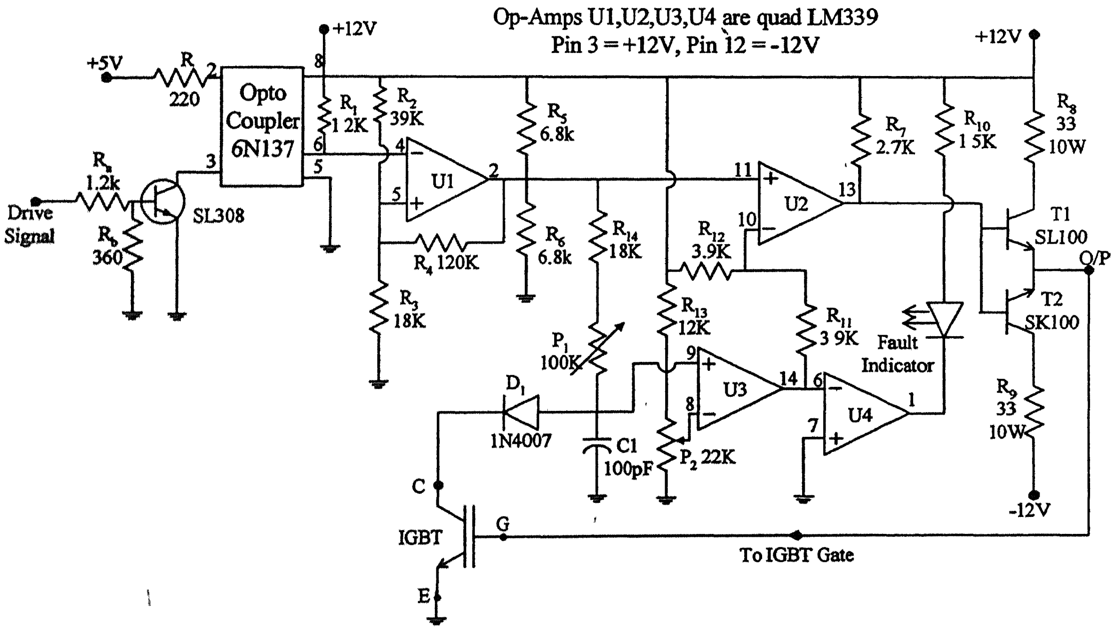


Fig. 3.8 Gate driver circuit

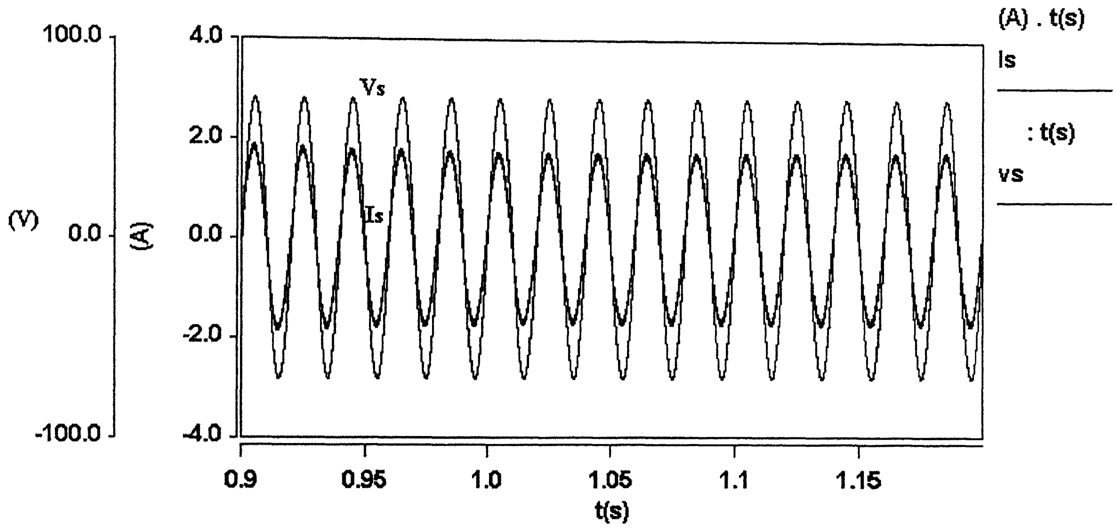
Fig. 3.8.a Experimental set up of single stage Synchronous Link Converter

3.7 Simulation and Experimental Results

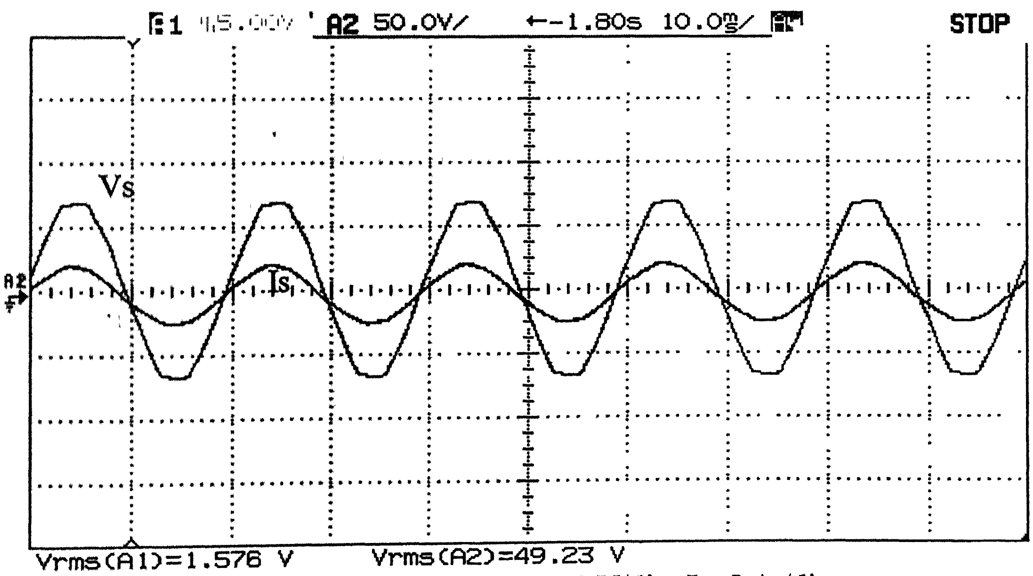
In this section the simulated and experimental results of a single phase synchronous link converter operated at three distinct switching frequencies are presented. Unity power factor operation is achieved at all switching frequencies. Figs 3.9-3.17 give the results for 5 kHz switching frequency for different load conditions. Fig. 3.9 gives simulated and experimental results of source voltage and source current for the synchronous link converter. Fig 3.17 gives the simulated and experimental harmonic spectrum of source current.

Figs 3.18-3.21 give results for 450Hz switching frequency for various load conditions. Fig 3.19 gives the unity power factor operation of synchronous link converter at steady state. Figs 3.22-3.25 give results for 750 Hz switching frequency. Fig 3.23 gives the unity power factor result at this switching frequency. Figs 3.21 & 3.25 gives the simulated and experimentally obtained harmonic spectrum of source current at 450 Hz and 750 Hz switching frequencies respectively. As expected the dominant harmonics appeared at well defined frequencies depending upon the switching frequencies. For 750 Hz switching frequency operation, the dominant harmonics appeared around 1500 Hz frequency and for 450 Hz operation the dominant harmonics appeared around 900 Hz. The simulated results are well in agreement with the experimental results.

3.7.1 For switching frequency 5 kHz



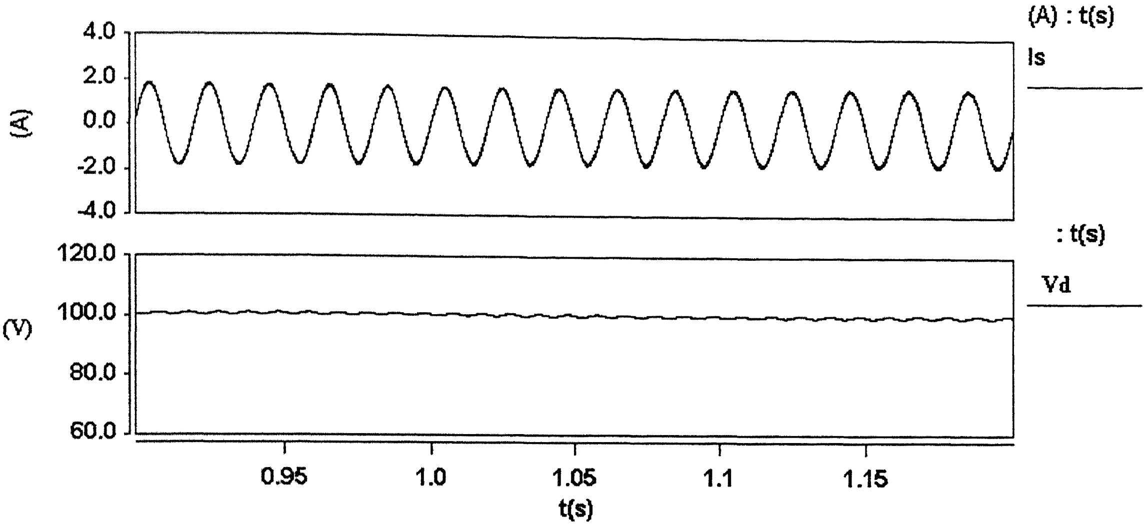
(a) Simulated wave form



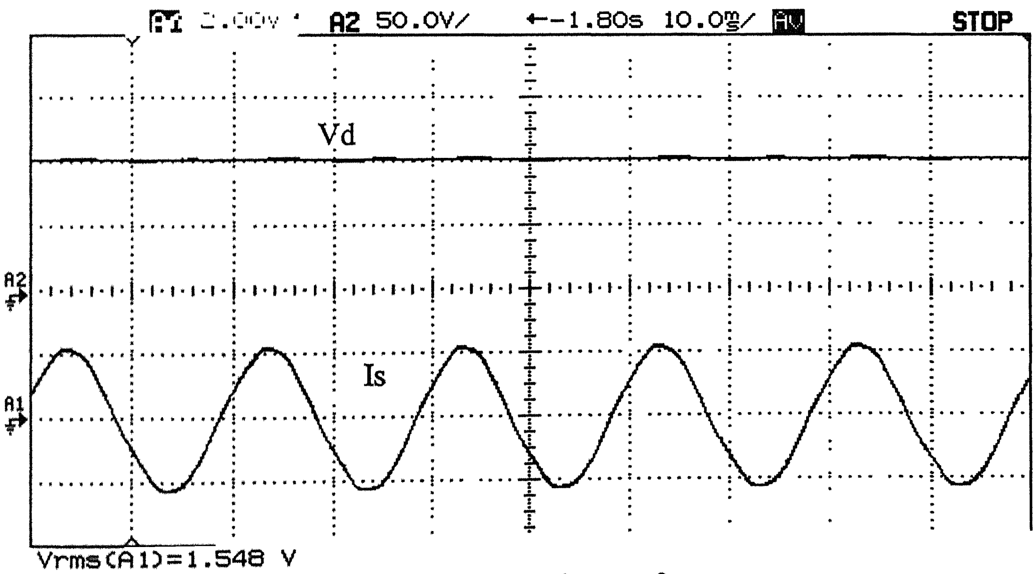
Scale - x-axis:10ms/div, Vs: 50 V/div, Is: 5 A /div

(b) Experimental wave form

Fig. 3.9 Steady State input current and input voltage waveform



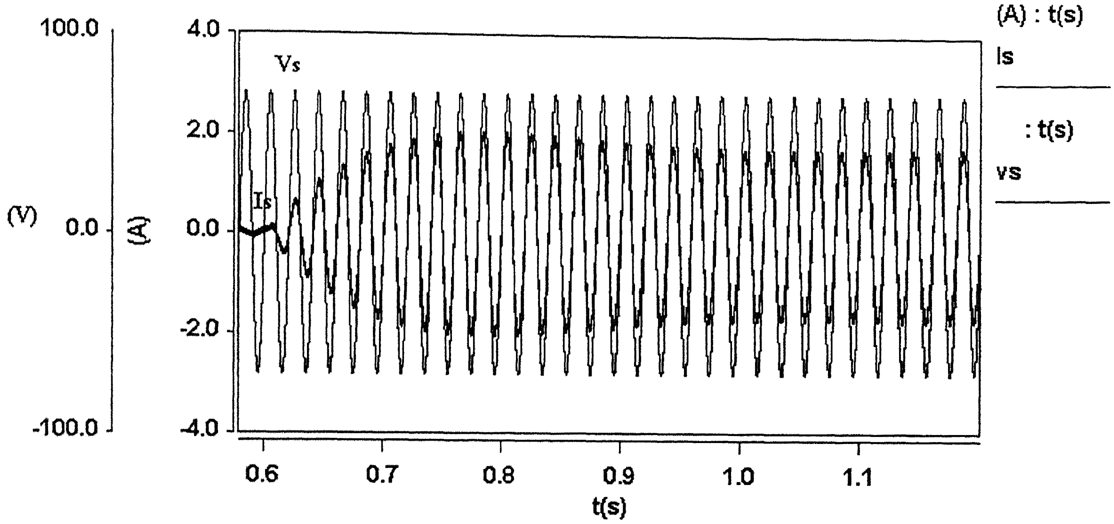
(a) Simulated Waveform.



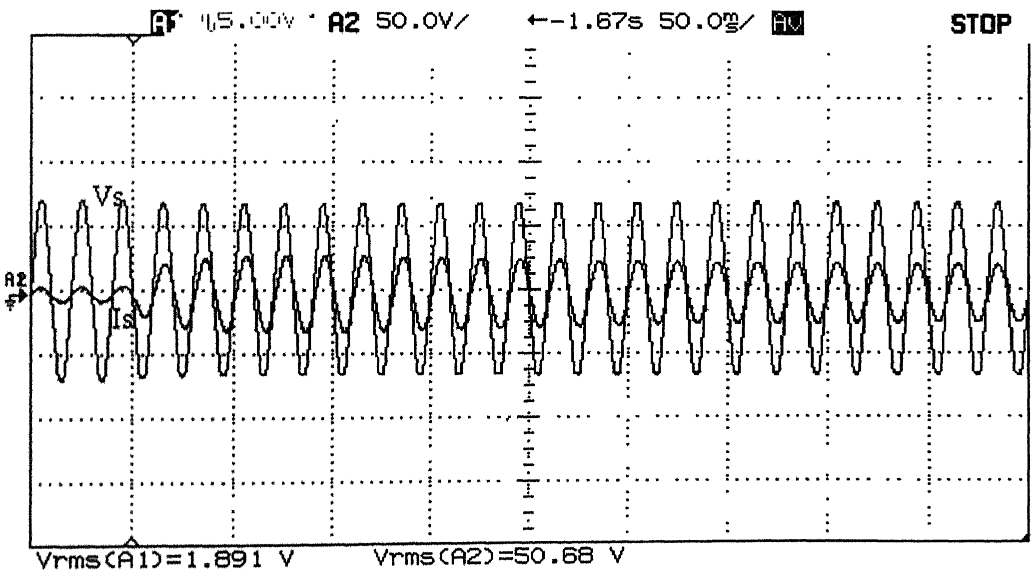
(b) Experimental wave form

Scale - x-axis: 10 ms/div, Is: 2 A /div, Vd: 50 V/div

Fig. 3.10 Supply current and dc link voltage at steady state



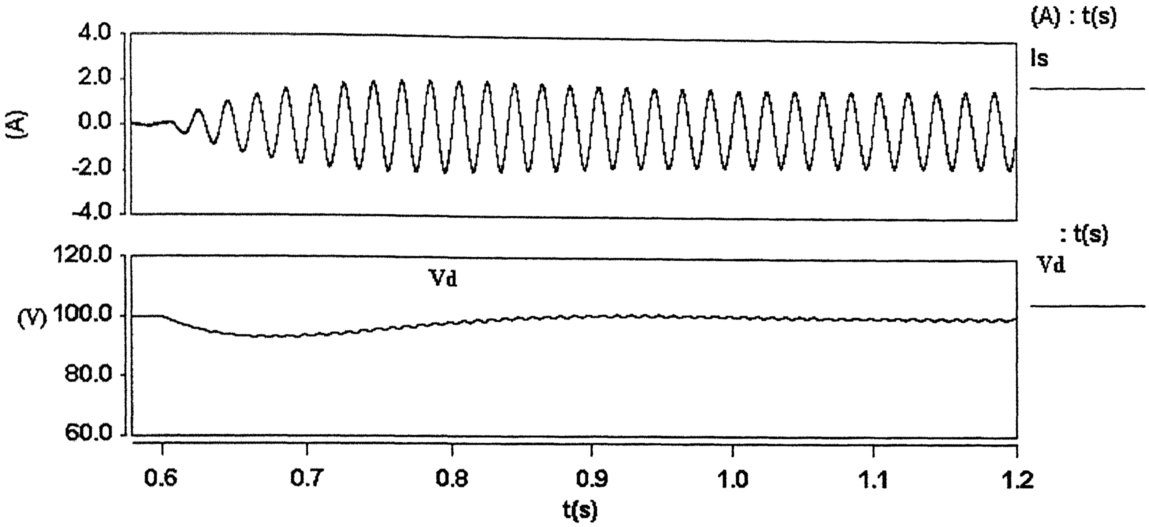
(a) Simulated wave form



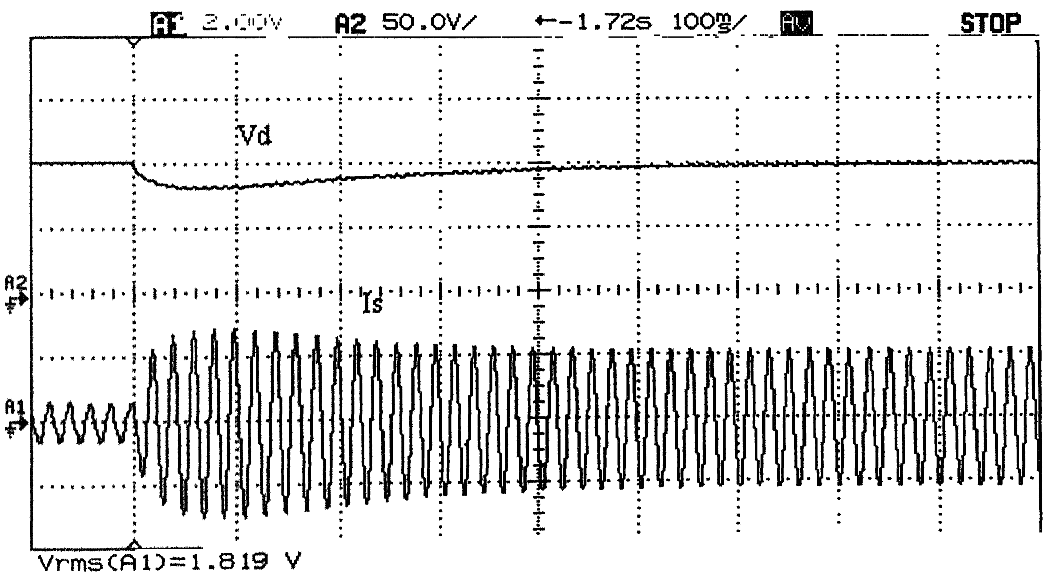
Scale - x-axis: 50ms/div, Vs: 50 V/div, Is: 5 A/div

(b) Experimental wave form.

Fig. 3.11 Supply Current and Voltage during switching on load



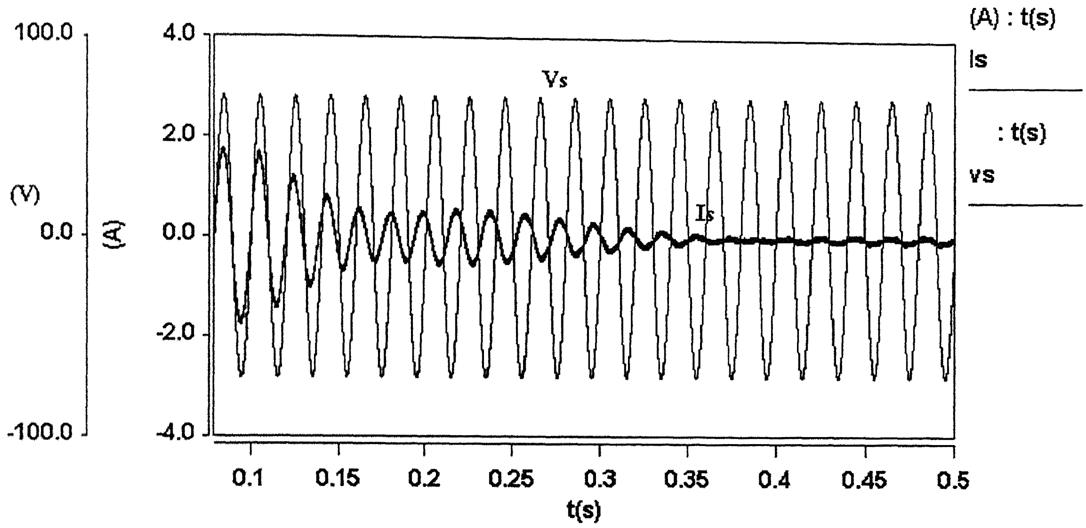
(a) Simulated wave form



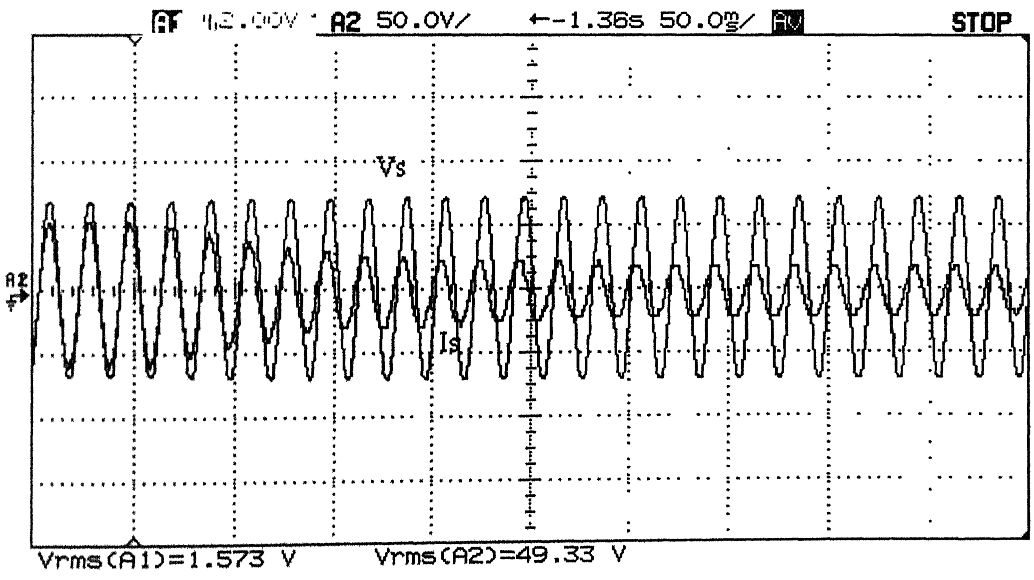
Scale-x-axis: 0.1 sec/div, Vd: 50 V/div, Is: 2 A/div

(b) Experimental wave form

Fig. 3.12 Current and dc link voltage wave forms during switching on load



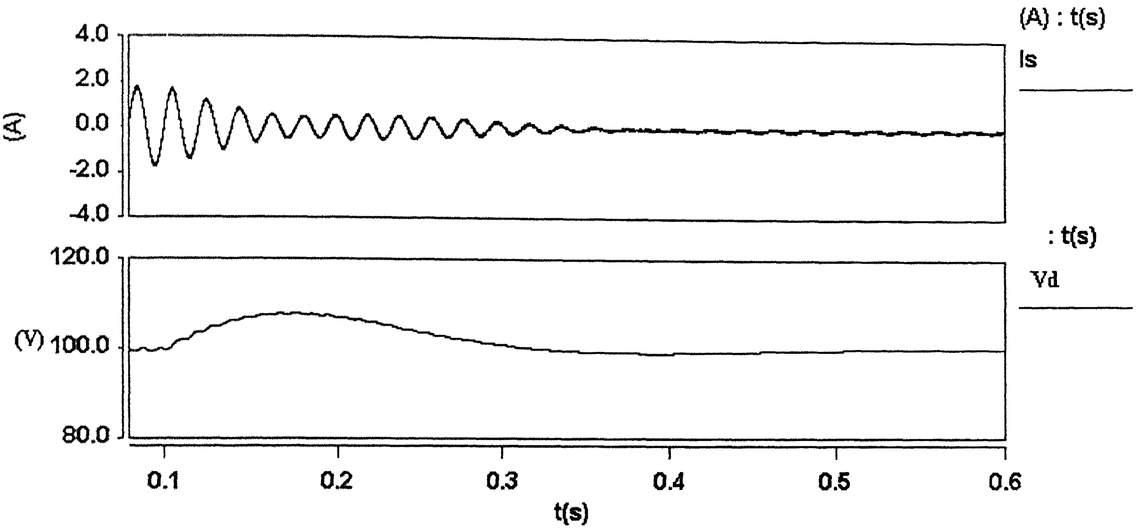
(a) Simulated wave form



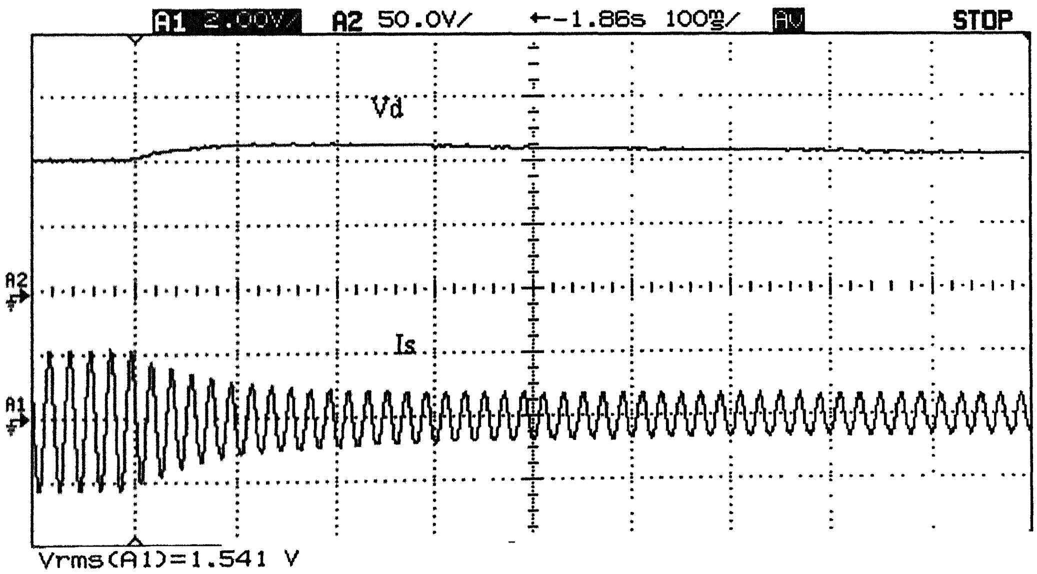
Scale - x-axis: 50 ms/div, Vs: 50 V/div, Is: 2A/div

(b) Experimental wave form

Fig. 3.13 Supply current and voltage waveforms during switching off load



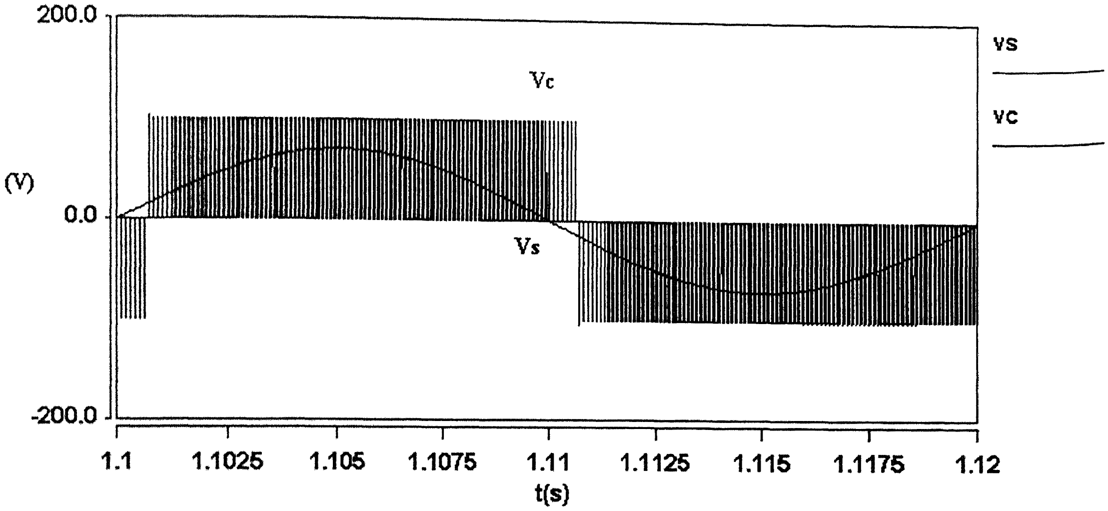
(a) Simulated wave form



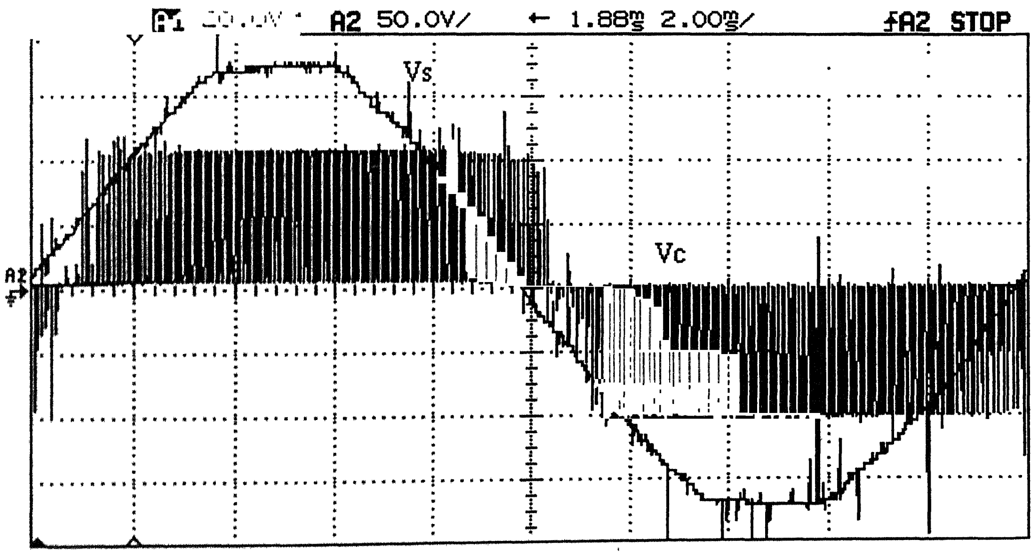
Scale - x-axis: 100 ms/div, Vs: 50 V/div, Is: 2A/div

(b) Experimental wave form

Fig. 3.14 Supply current and voltage waveforms during switching off load



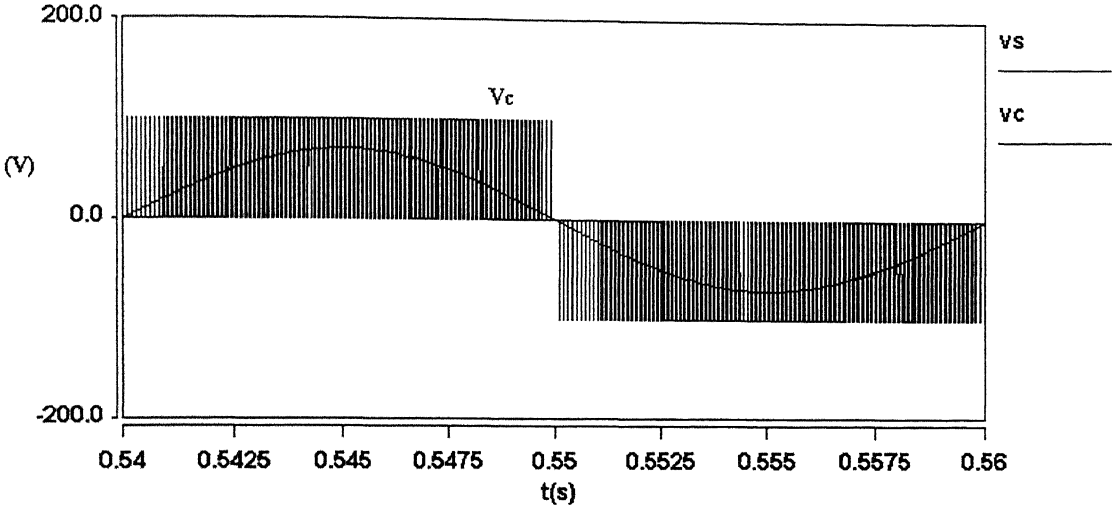
(a) Simulated wave form



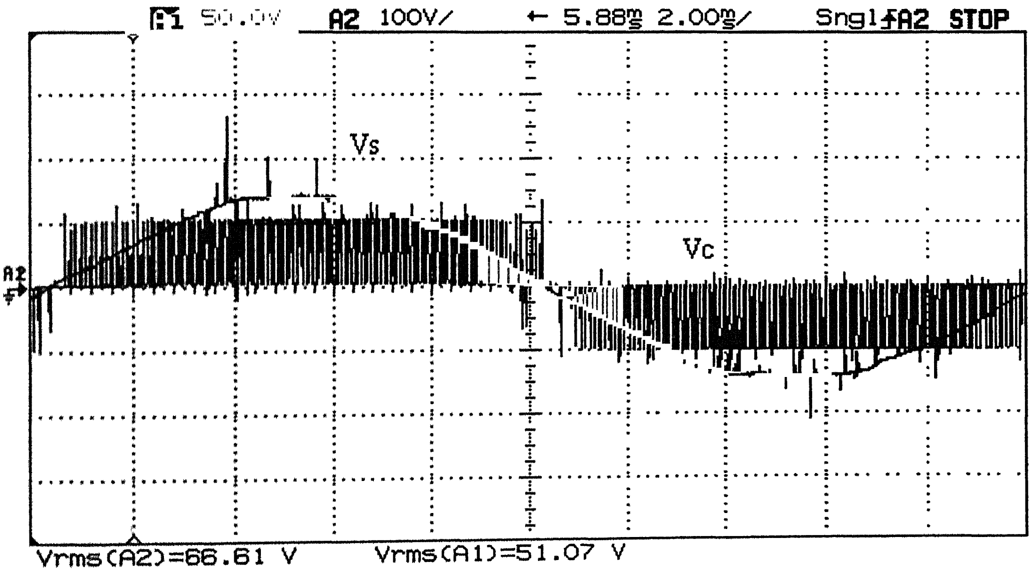
Scale - x-axis: 2 ms/div, Vs: 20 V/div, Vc: 50V/div

(b) Experimental wave form

Fig. 3.15 Supply voltage and converter input voltage during full load



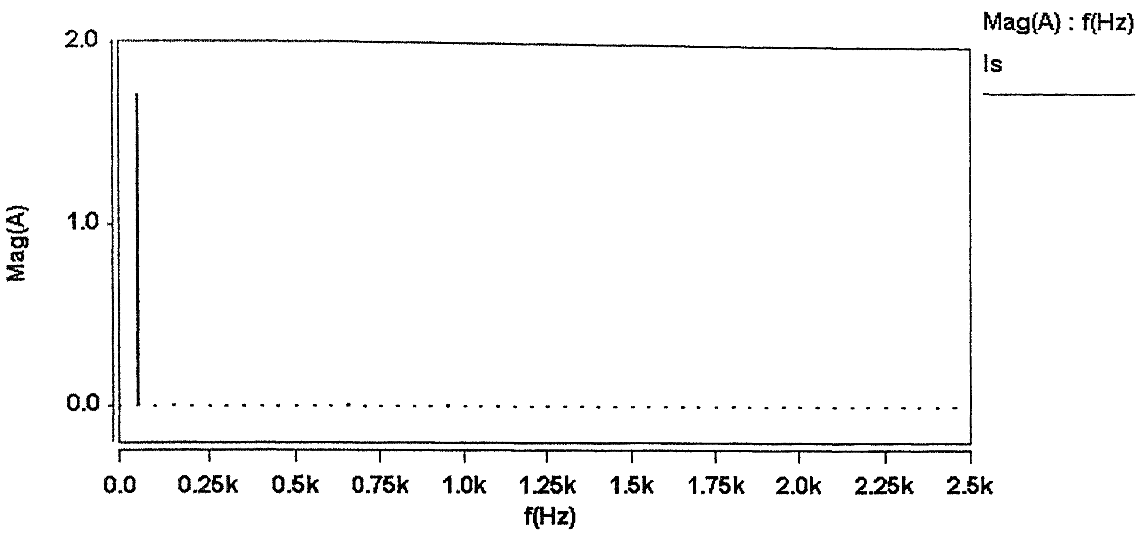
(a) Simulated wave form



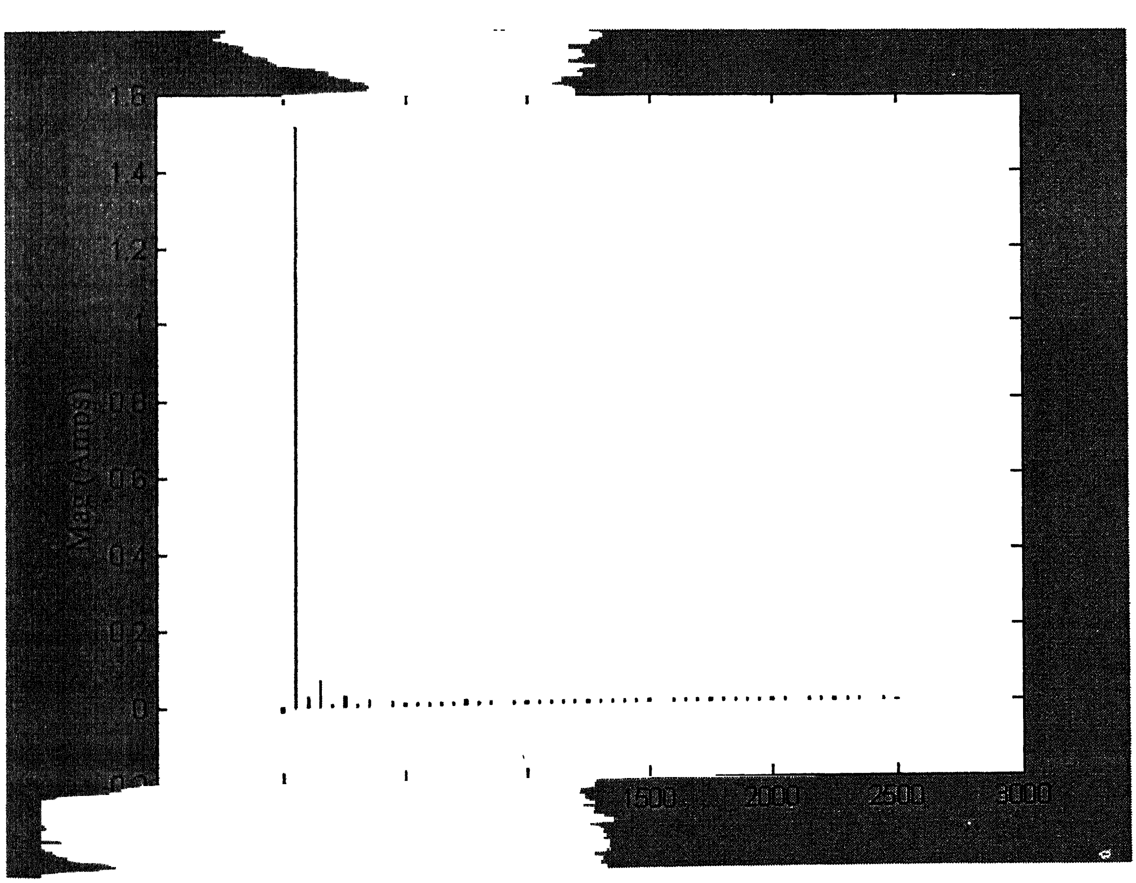
Scale - x-axis: 2 ms/div, Vs: 50 V/div, Vc: 100V/div

(b) Experimental wave form

Fig. 3.16 Supply voltage and converter input voltage at no load



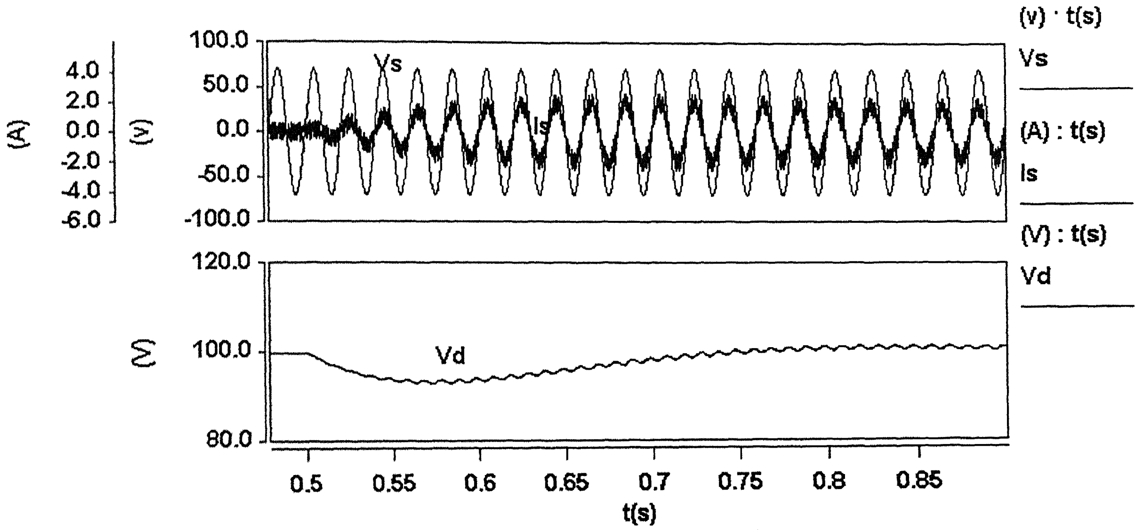
(a) Harmonic spectrum of supply current (Simulated)



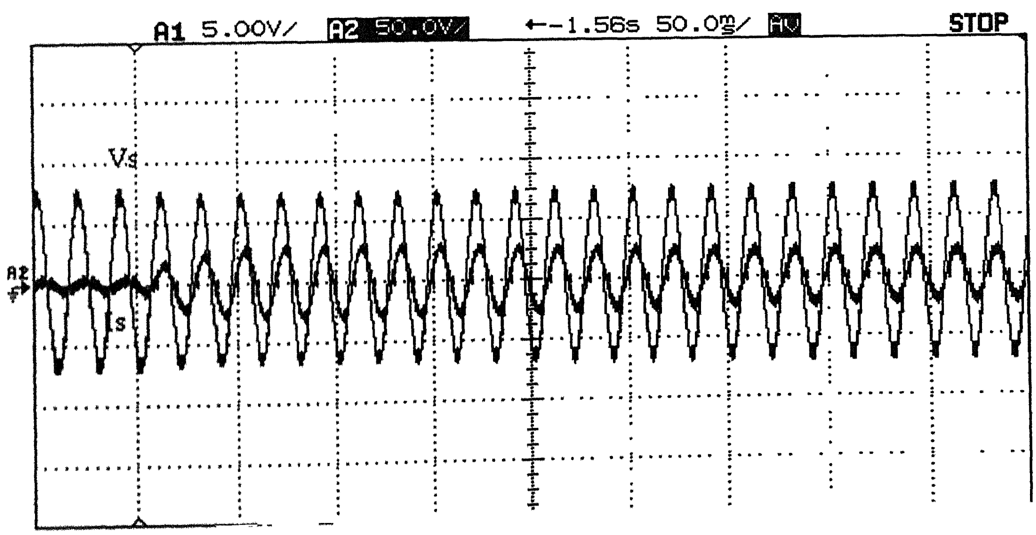
(b) Harmonic spectrum of supply current (Experimental)

Fig. 3.17 Harmonic spectrum of supply current

3.7.2 For switching frequency 450 Hz

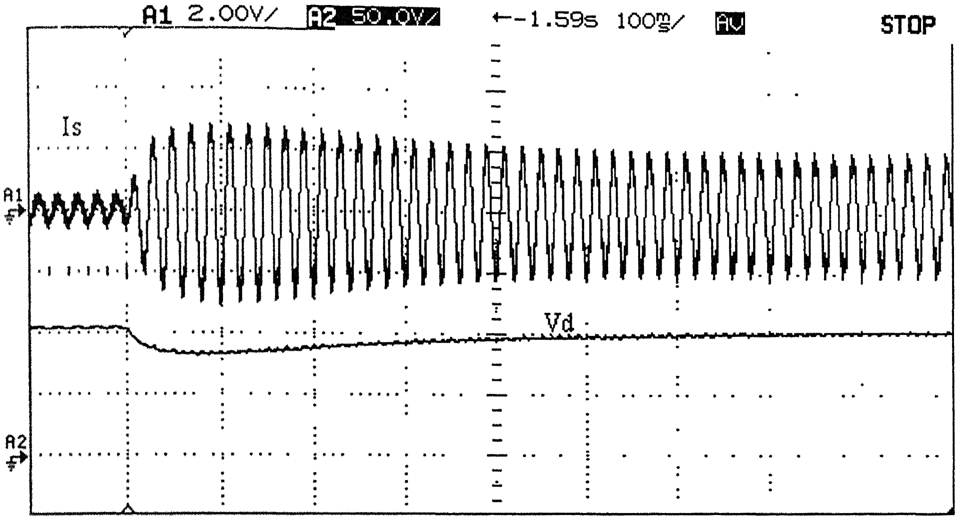


(a) Simulated waveform



Scale - x-axis: 50 ms/div, Vs: 50 V/div, Is: 5 A/div.

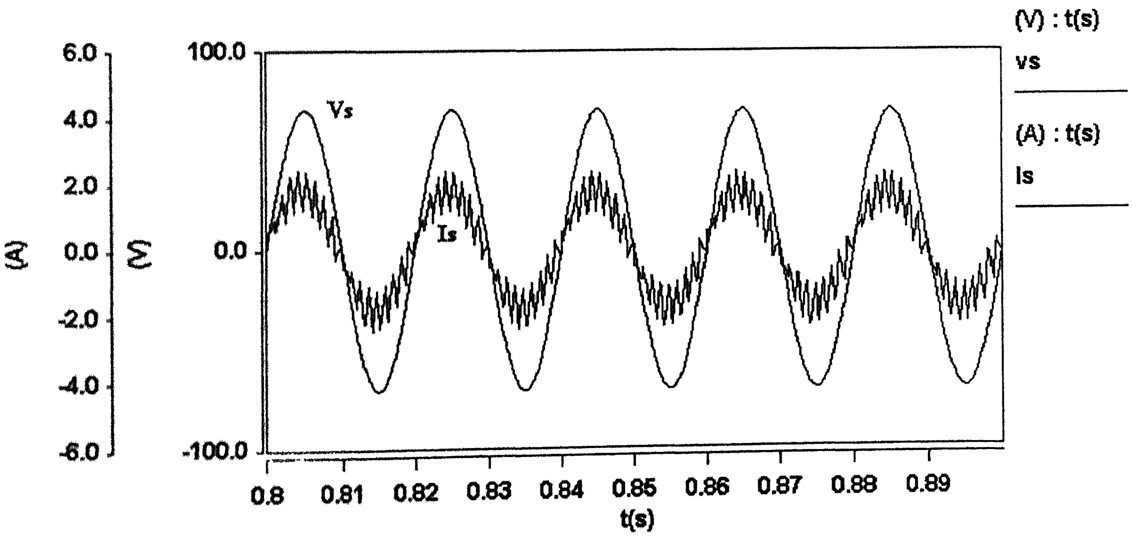
(b) Experimental wave form of Input current (Is) and Voltage (Vs)



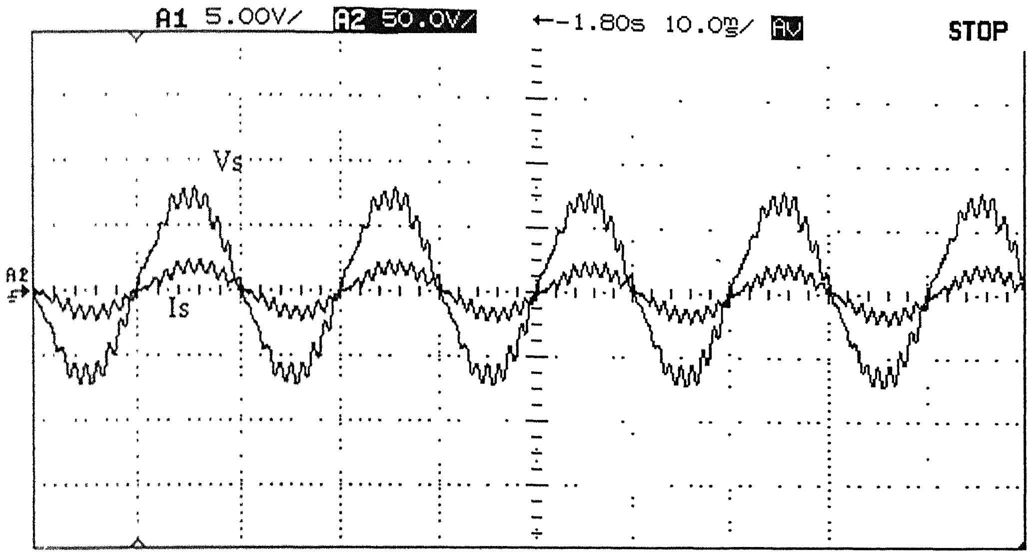
Scale - x-axis: 0.1s/div, Vd: 50 V/div, Is: 2A/div

(c) Experimental wave form of input current (Is) and dc link voltage (Vd)

Fig. 3.18 Supply current, voltage and dc link voltage during switching on load



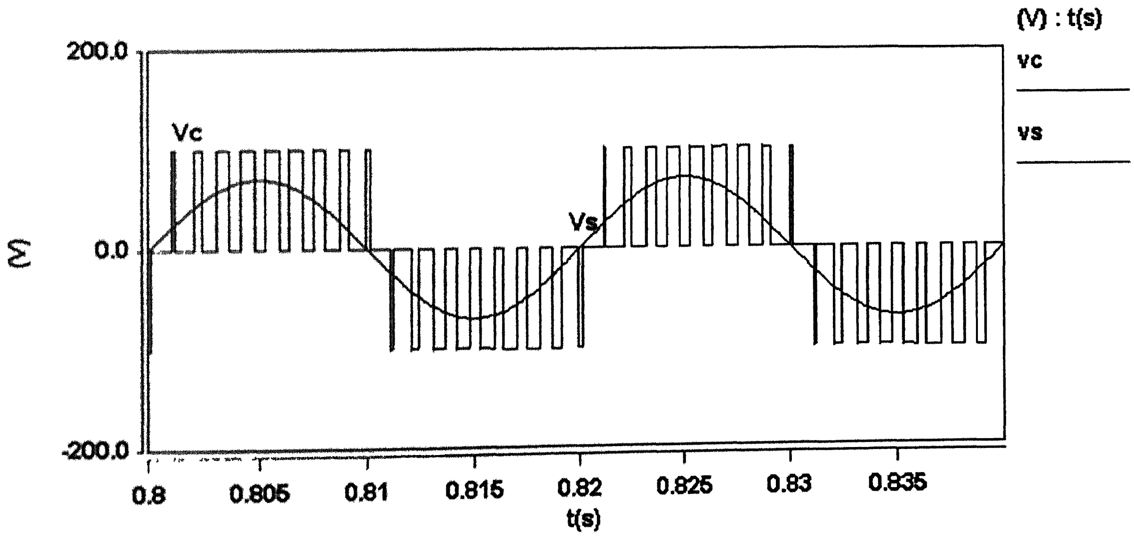
(a) Simulated wave form of voltage (Vs) and input current (Is) at steady state

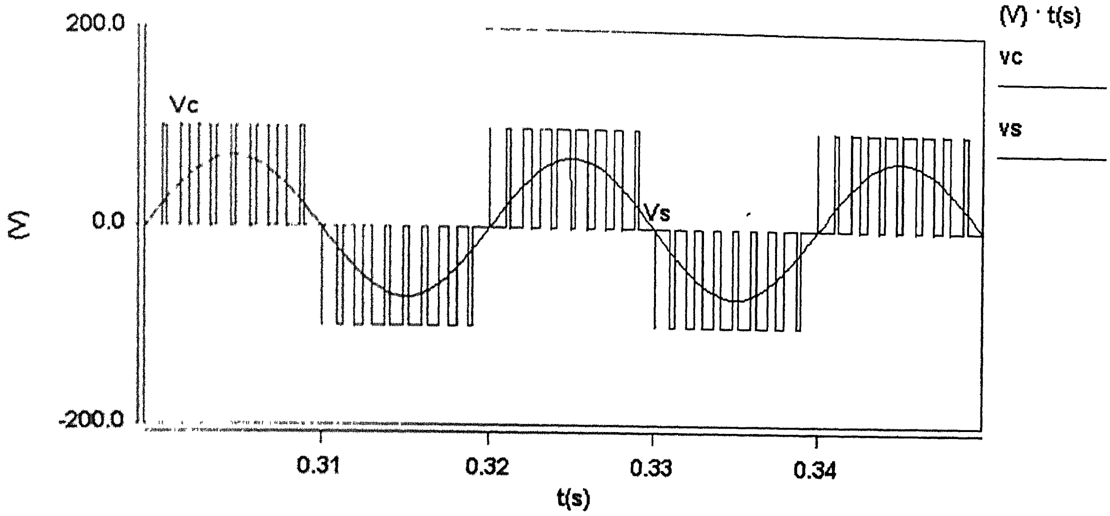


Scale - x-axis: 10ms/div, Vs: 50 V/div, Is: 5 A/div

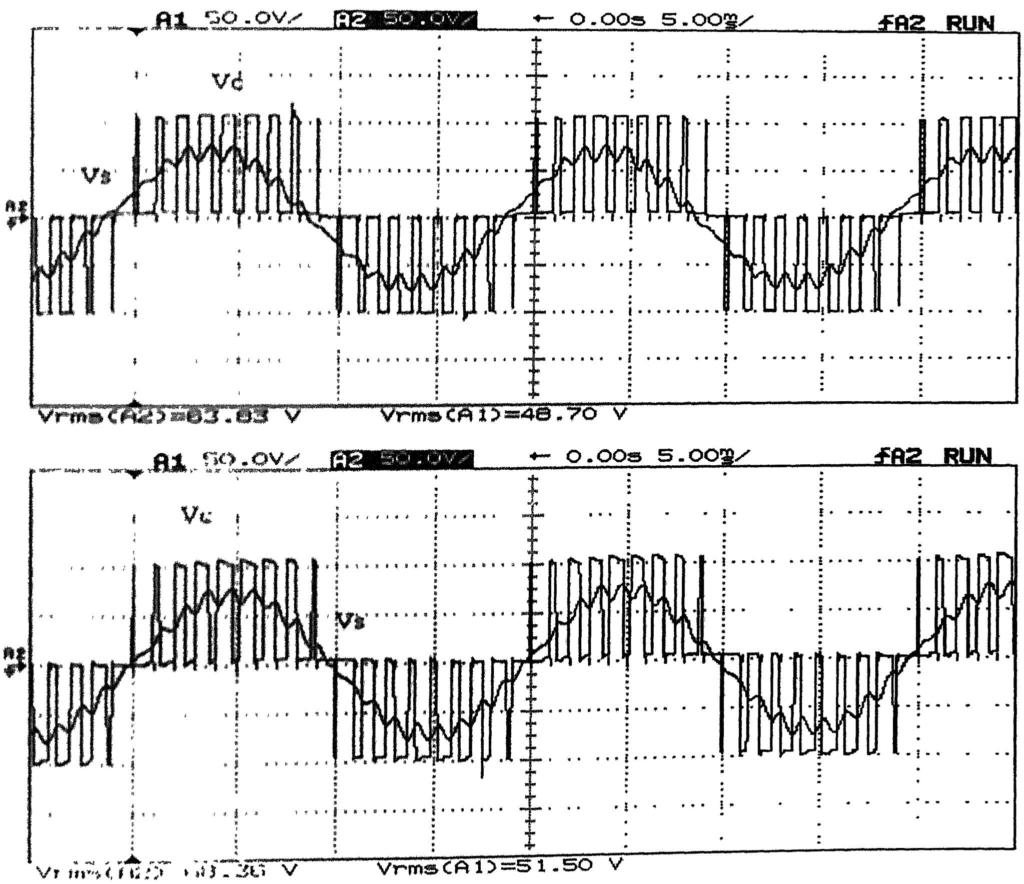
(b) Experimental waveform of Is and Vs during steady state.

Fig. 3.19 Supply voltage and current during steady state





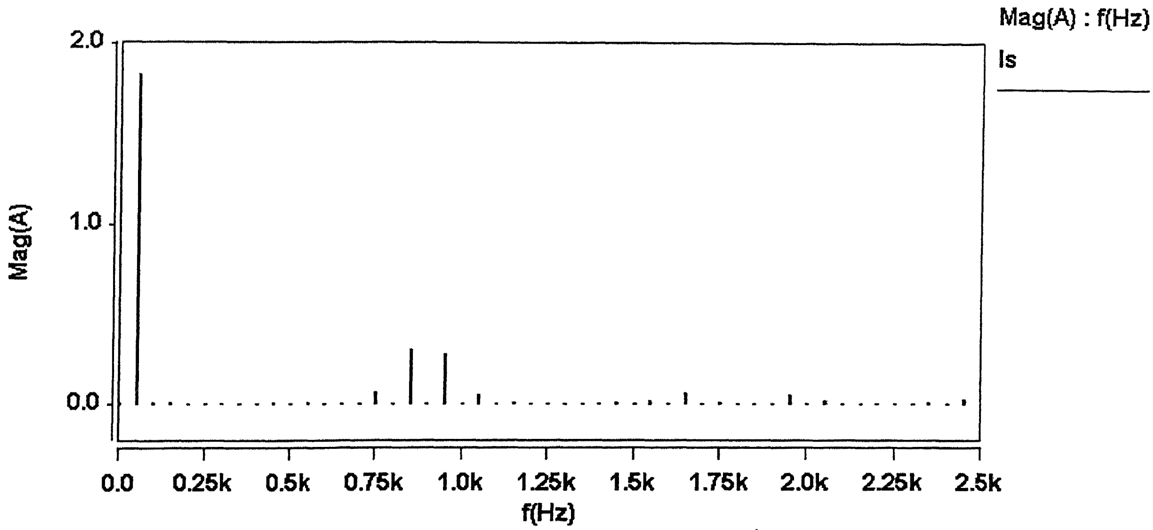
(a) Simulated wave forms of converter input voltage (Vc) and supply voltage (Vs).



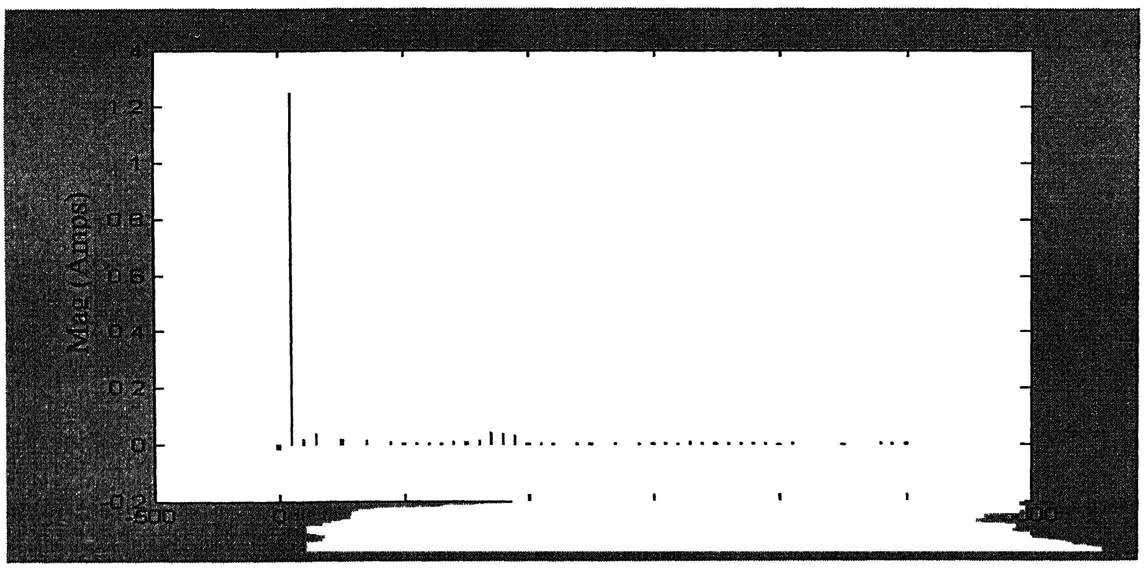
Scale - x-axis: 5ms/div, Vs: 50 V/div, Vc: 50 V/div.

(b) Experimental wave forms of converter input voltage (Vc) and supply voltage (Vs)

Fig. 3.20 Supply voltage and Converter input voltage at full load and no load



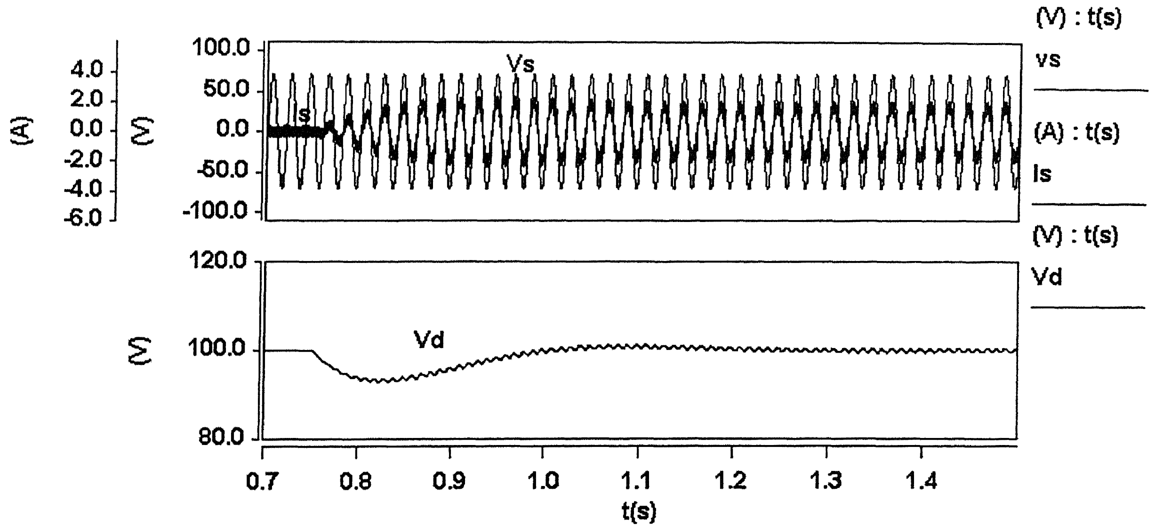
Harmonic spectrum of supply current (Simulated)



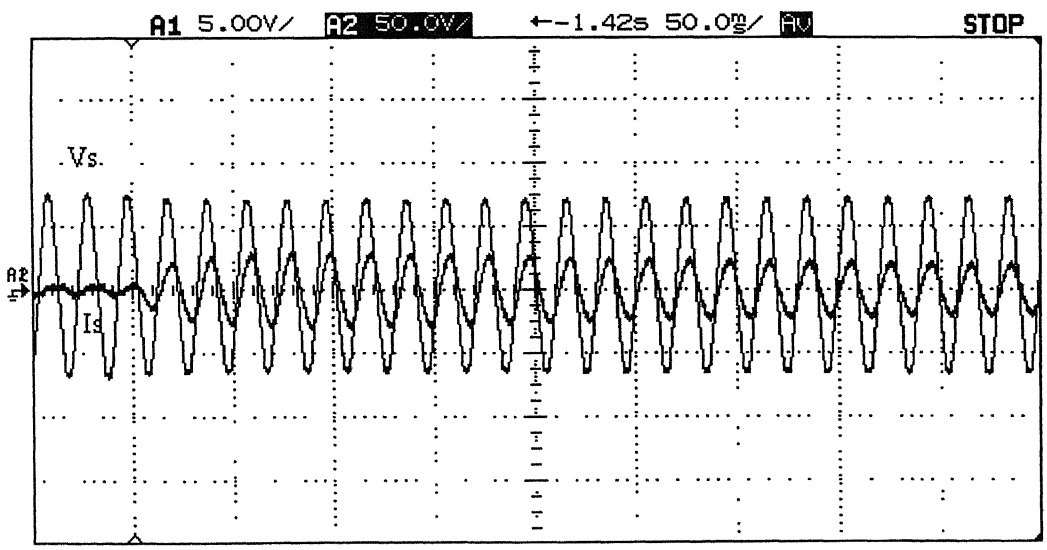
Harmonic spectrum of supply current (Experimental)

Fig. 3.21 Harmonic spectrum of supply current

3.7.3 For switching frequency 750 Hz

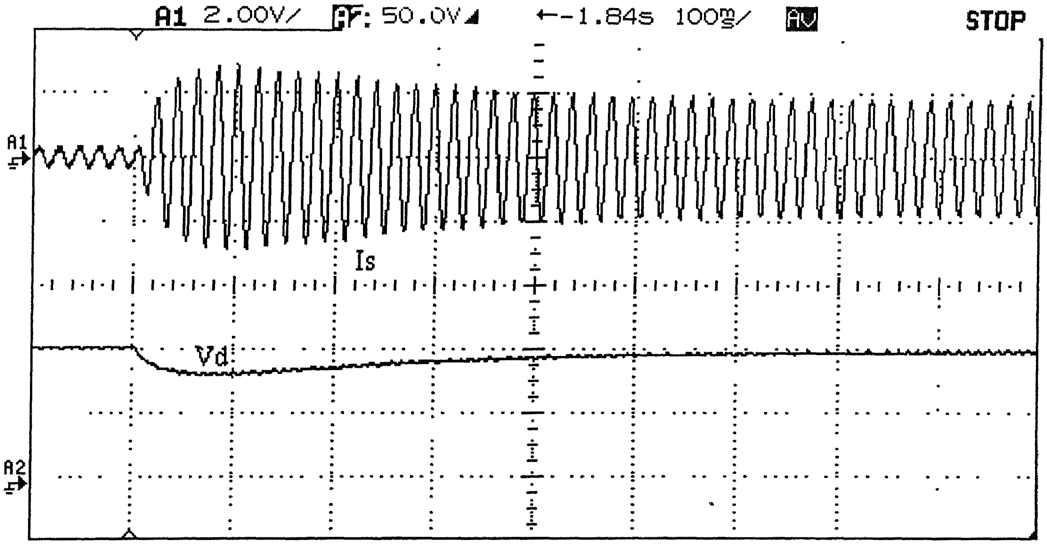


(a) Simulated wave form



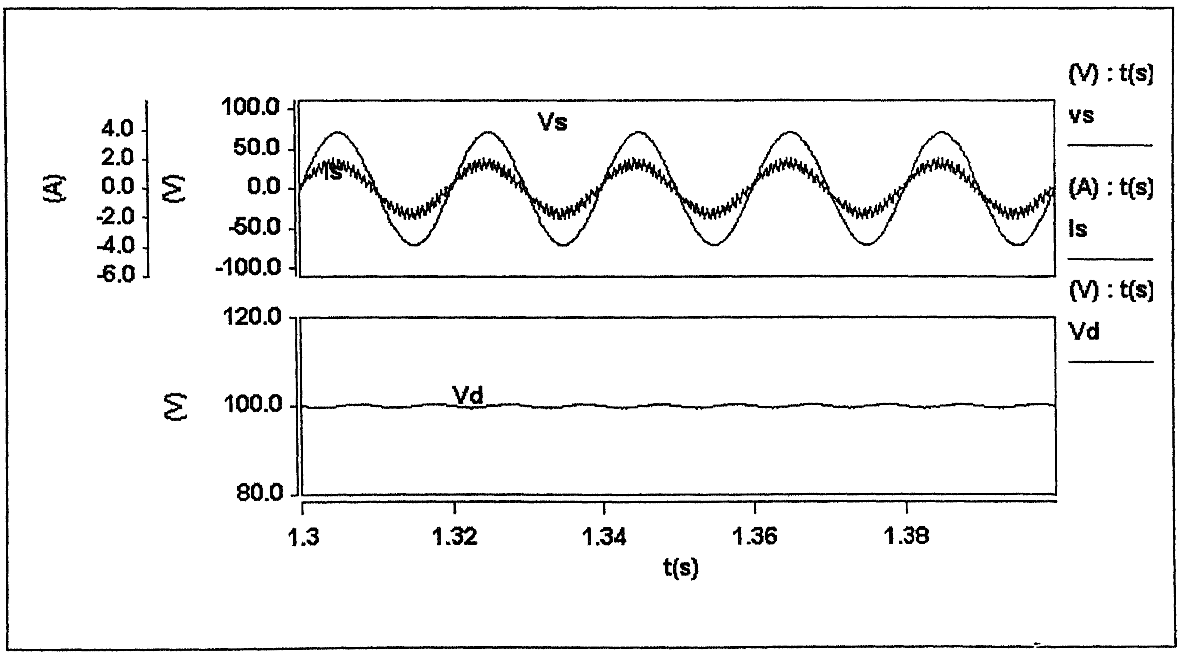
(b) Experimental wave forms of supply voltage (Vs) and current (Is)

Scale - x-axis: 50ms/div, Vs: 50 V/div, Is: 5 A/div.

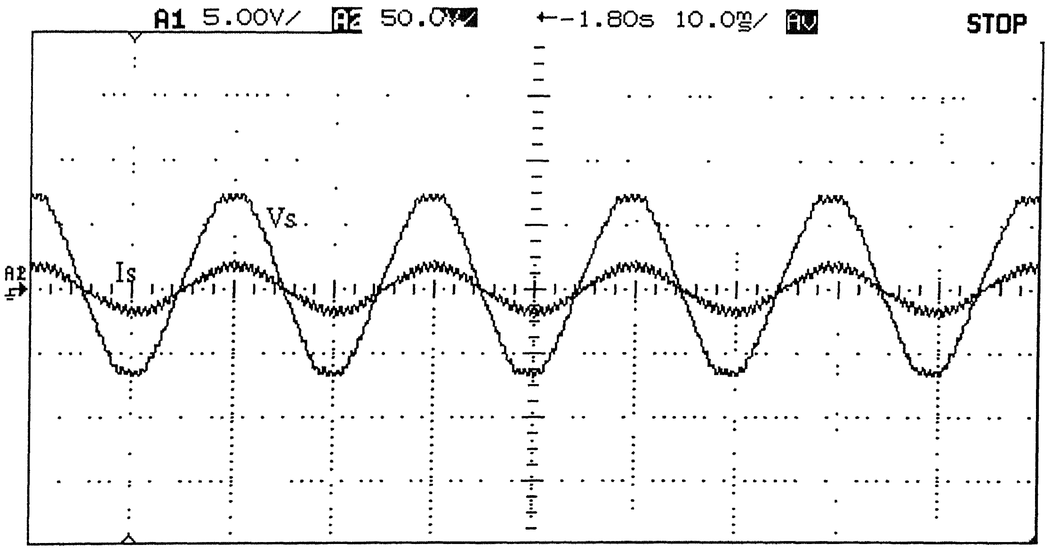


(c) Experimental wave forms of dc link voltage (Vd) and supply current (Is)

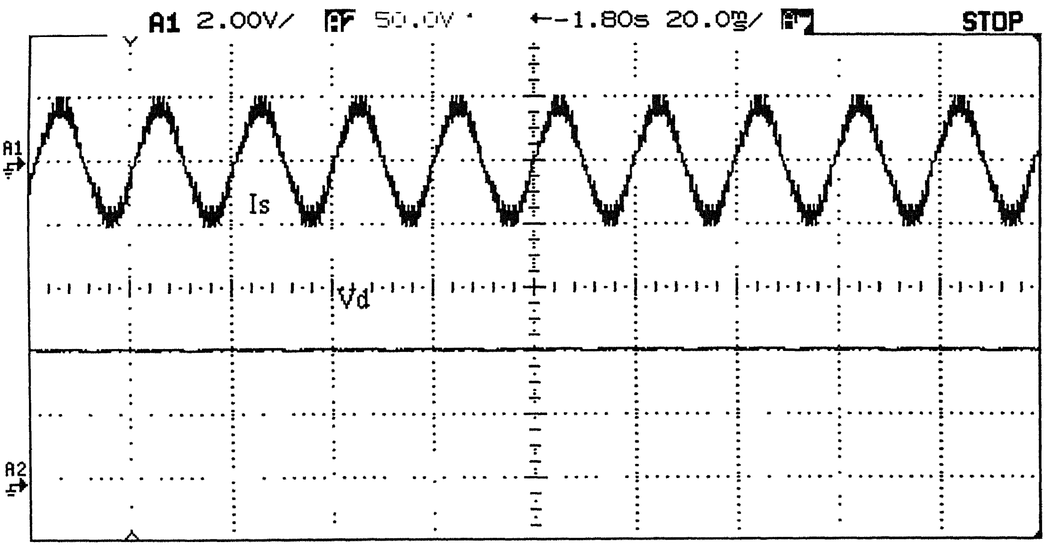
Fig. 3.22 Supply current, voltage and dc link voltage during switching on load



(a) Simulated wave form of supply voltage (Vs), current (Is), dc link voltage (Vd)



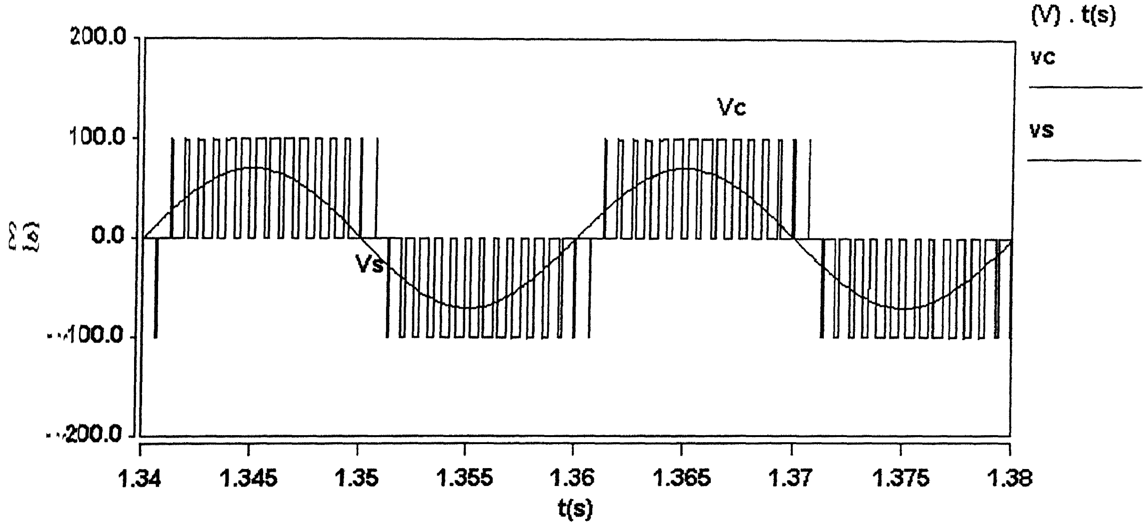
Scale - x-axis: 10ms/div, Vs: 50 V/div, Is: 5 A/div

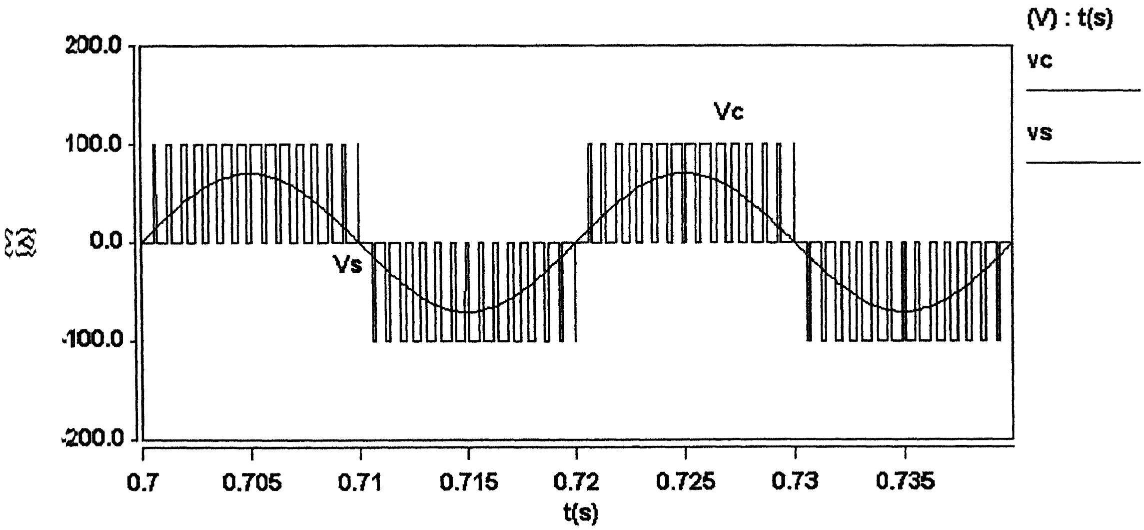


Scale - x-axis: 20ms/div, Vs: 50 V/div, Is: 2 A/div

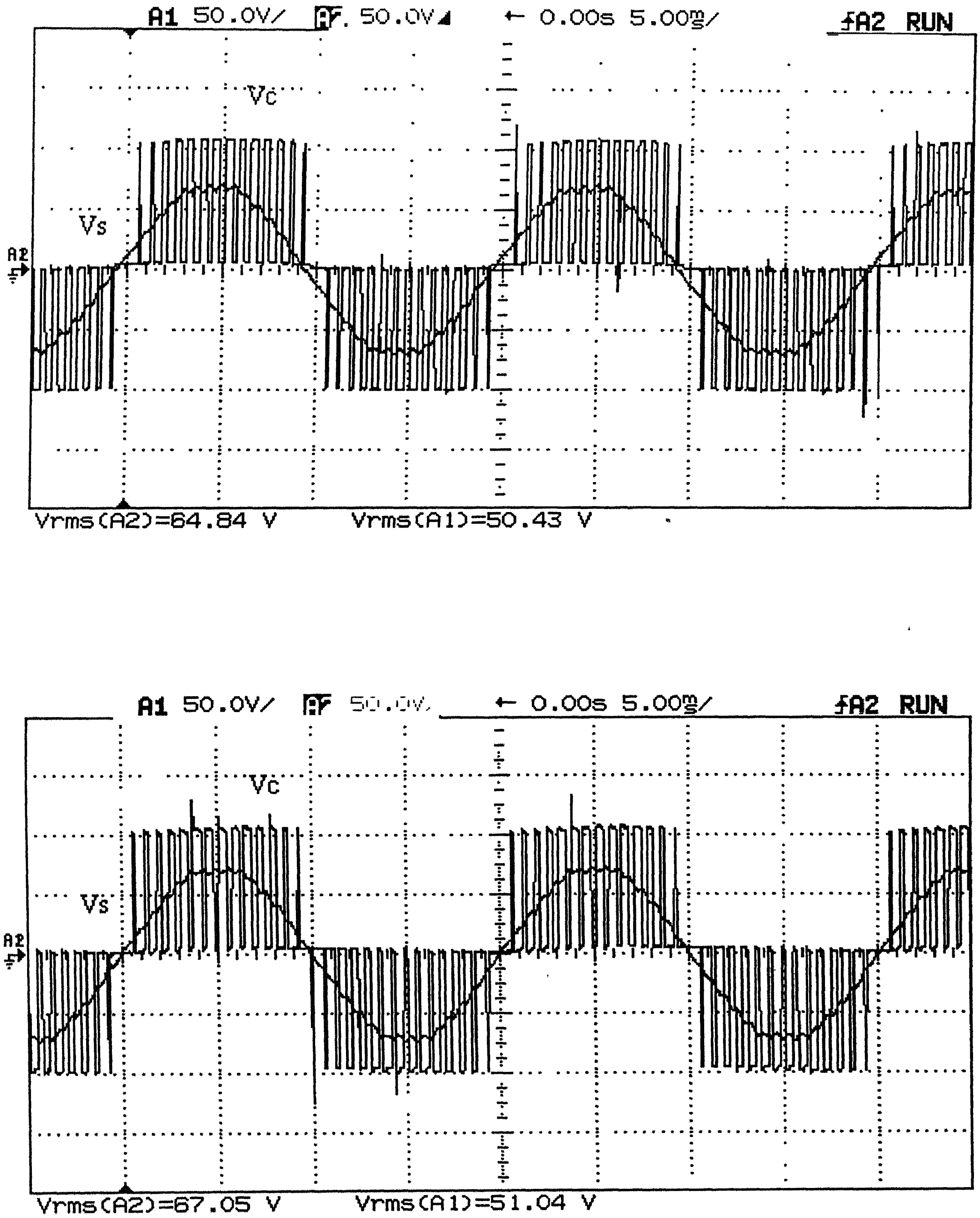
(b) Experimental wave forms of supply current (Is), voltage (Vs), dc link voltage (Vd)

Fig. 3.23 Supply voltage, current and dc link voltage during steady state





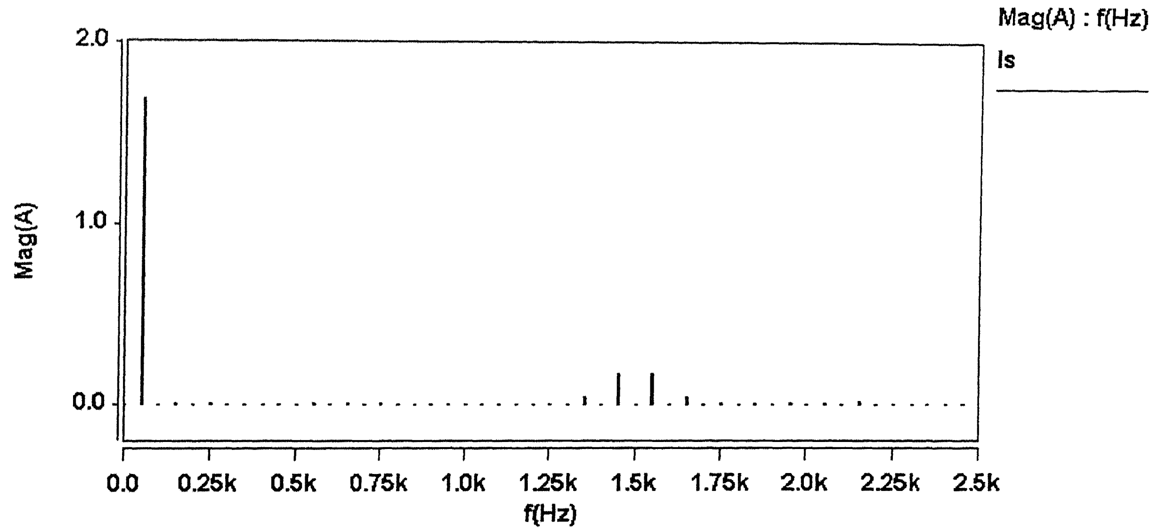
(a) Simulated wave forms of converter input voltage (Vc) and supply voltage (Vs).



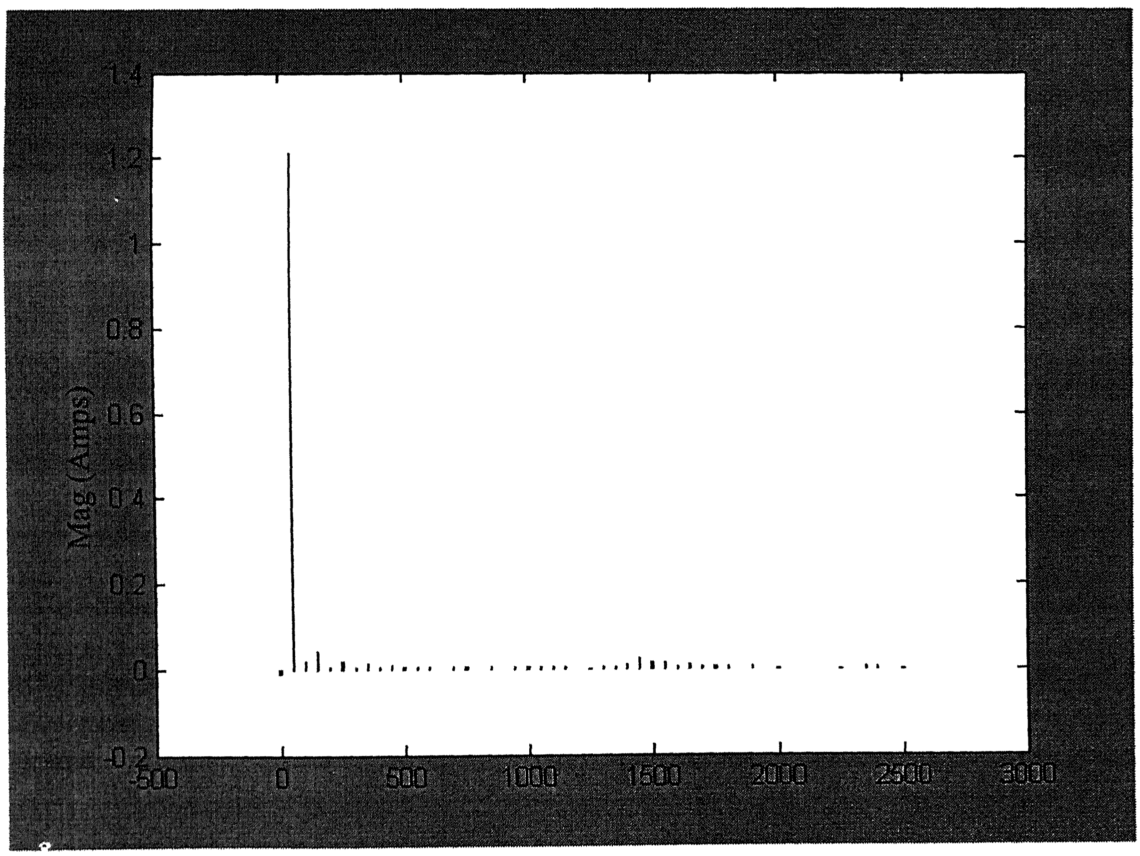
Scale - x-axis: 5ms/div, Vs: 50 V/div Vc: 50 V/div

(b) Experimental wave forms of supply voltage (Vs) and converter input voltage (Vc)

Fig. 3.24 Supply voltage and Converter input voltage at full load and no load



Harmonic spectrum of supply current (simulated)



Harmonic spectrum of supply current (Experimental)

Fig. 3.25 Harmonic spectrum of supply current

3.8 Conclusion

Due to their simple construction, design, capability for bidirectional power flow, reduced input line current harmonics and unity power factor operation the Synchronous Link Converters are widely used as front end converters in regenerative ac drives. When Synchronous Link Converters are used as front end converter in ac regenerative Traction drives, due to their inherent ability to operate with reduced harmonic currents, the interference to telecommunication and track circuit reduces. Further the unity power factor operation of the converter will results in higher efficiency. Due to the use of PWM control in indirect current control method, the dominant harmonics appear at well defined frequencies. So, passive filters can be designed to suppress these harmonics from entering into the supply.

Chapter 4

Single and Dual Synchronous Link Converter Topologies for Modern ac Electric Traction system

4.1 Introduction

In the field of electric traction, dc motors have been in use since long. However at present the three phase ac drive is becoming very common and significant for the modern electric traction drive systems. These drive systems are equipped with asynchronous traction motors featuring easy maintenance, high reliability and compact design. Such systems require converters on the motor coaches / locomotives, which rectify power from ac to dc and PWM inverters for converting the dc into three phase ac for feeding the asynchronous traction motors. In a modern regenerative single phase 25 kV traction drive Synchronous Link Converter can be used as a front-end converter, featuring an ac input current which is almost in phase with the supply voltage and controllable to almost sinusoidal waveform. Also it meets most of the requirements of the front-end converter systems for the Electric traction systems. In this chapter simulations carried to study the performance of Synchronous Link Converter as traction front-end converter system are presented. Simulations for both single stage and dual stage were presented.

4.2 Requirements of the Front-end Converters for Electric Traction Systems

1. The front-end converter system should ensure a near unity power factor.
2. The converters should not cause intolerable level of interference to the track circuits and the telecommunication equipments.

3. The converters should be designed in a way to keep the psophometric disturbance current, the dc component, the audio frequency components and the high frequency components within the enforced limits given in table 4.1.
4. The front-end converters should ensure four quadrant operation and the regenerative braking should be available from the maximum speed range up to near stand still.
5. The converter system should be provided with the necessary control to operate under wide fluctuations of catenary voltage fluctuations. With Indian railways, the power supply for over head catenary is 25 kV, 1-Φ, 50 Hz. The 25 kV being nominal voltage of the system, the variations in supply voltage is from 17.5 kV to 30.0 kV.
6. The converter should be capable to permit continuous operation of super dense crush loaded train (the maximum load which will come on the driving axle, under given operating conditions).
7. The converter rating should be designed by taking consideration of entire system by considering the adhesion co-efficient, power requirement for the operation of motor coaches on given gradient. The voltage of switching devices used should be chosen to keep at least 25% margin available after taking into consideration the dc link voltage and the voltage spikes on account of inductance and capacitance in the circuit.

4.3 Psophometric Current

It is usual practice to install, the telecommunication lines in parallel along the track. In the case of electric traction, the harmonic currents flowing in overhead catenary

cause interference in the telecommunication lines. The depth of interference is accessed by using a factor called psophometric disturbance current. It is assessed by using an equivalent interfering current (J_p), where J_p is given by the following equation

$$J_p = \sqrt{\sum_{n=1}^{59} (S_n . I_n)^2}$$

Where, I_n is the nth harmonic current in supply current and S_n is the noise assessment coefficient.[7]

Table 4.1 Enforced limits

Particular	Enforced Limits
Psophometric current	$\leq$ 10.0 A
DC component of current	$\leq$ 4.7 A
Second harmonic component of current	$\leq$ 8.7 A
Audio frequency component 1650 – 1750 Hz 1950 – 2050 Hz 2250 – 2350 Hz 2550 – 2650 Hz	 $\leq$ 400 mA amplitude $\leq$ 400 mA amplitude $\leq$ 400 mA amplitude $\leq$ 400 mA amplitude
High frequency component 5050 – 5100 Hz	 $\leq$ 270 mA amplitude

The noise assessment co-efficient was established by the C.C.I.T.T (International Telegraph and Telephone Consultative Committee) in 1952. The noise assessment coefficient or the weightage factors for different frequencies are given in Appendix I. The variation of this weightage factor with the harmonic number is given in Fig. 4.1. Fig 4.1 suggests that the weightage factor is very small for low order harmonics and has a peak around 1000 Hz. There fore psophometric current depends mainly on the higher order

harmonics. These factors are to be considered in the weightage of Synchronous link converters for electric traction applications [7].

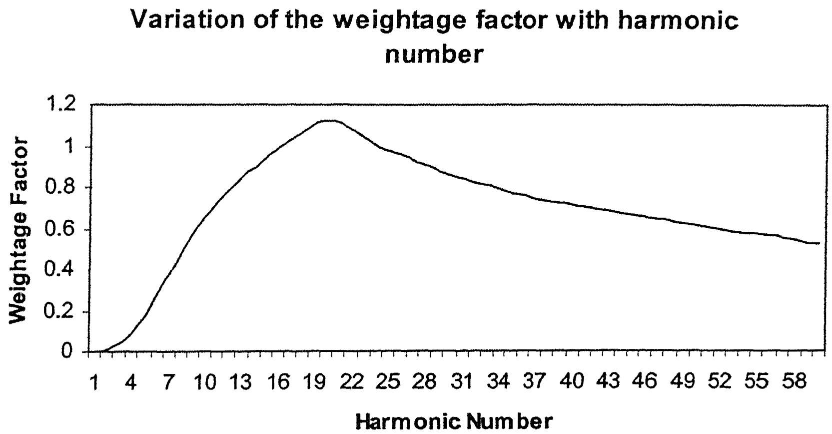


Fig. 4.1 Variation of weightage factor with harmonic number

In case of electric traction, it is essential that the converters operate at different power levels, with the minimal harmonic injection into over head catenary supply. As the power requirement is high low value of synchronous link inductance is necessary. In this traction system the synchronous link inductance is realized by utilizing the leakage reactance of transformer which has low value. Due to this low value the effect of varying power output results in the variation of modulation index over a narrow range. The magnitude of harmonic voltage at converter input may be assumed to be a constant, when the modulation index is varied over a narrow range. Hence the harmonic currents at input and hence psophometric current at the over head catenary remains constant.

4.4 Single and dual converter topologies

The front-end converter system is supplied from the single phase over head ac catenary through the pantograph and a step down transformer. The transformer has a single primary and winding and multiple secondary windings depending upon the number

of converter stages used. Fig. 4.2 shows a basic single stage synchronous link converter traction drive. In this topology the traction transformer has only single secondary winding. The synchronous link converter is operated in closed loop using indirect current control as discussed in 3.3.

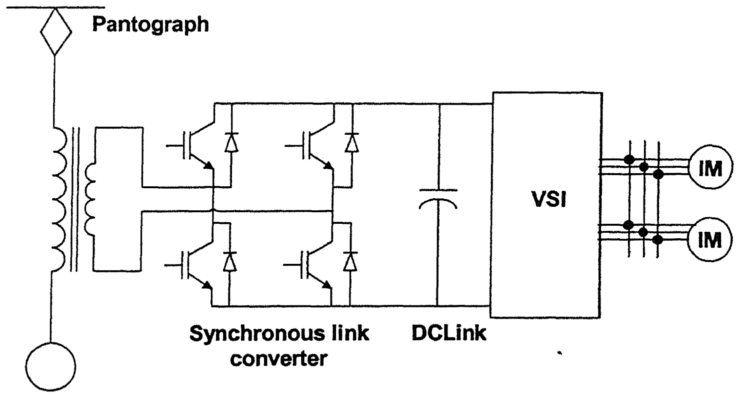


Fig. 4.2 Single Stage Synchronous Link Converter Topology

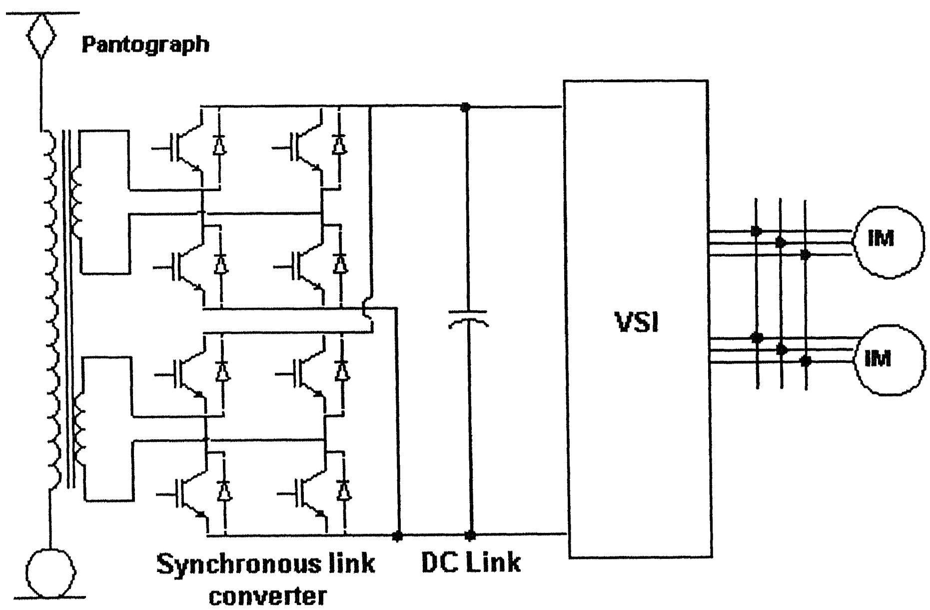


Fig. 4.3 Two Stage Synchronous Link Converter Topology

Fig. 4.3 shows a basic two stage synchronous link converter traction drive. In this topology the converters are operated in parallel. The pantograph is connected to primary of a step-down transformer with two secondary windings each feeding a synchronous link

converter. These converters feed a common dc link circuit. The dc link feeds PWM VSI inverter, which converts dc into three phase ac for feeding the asynchronous traction motors. Each of the two synchronous link converters is operated as an independent unit with a common modulating signal. The carrier signals of the individual converters are equally displaced within one half of the carrier period by angle $\pi/2$ radians. Fig. 4.4 gives the carrier signals for the converters I and II.

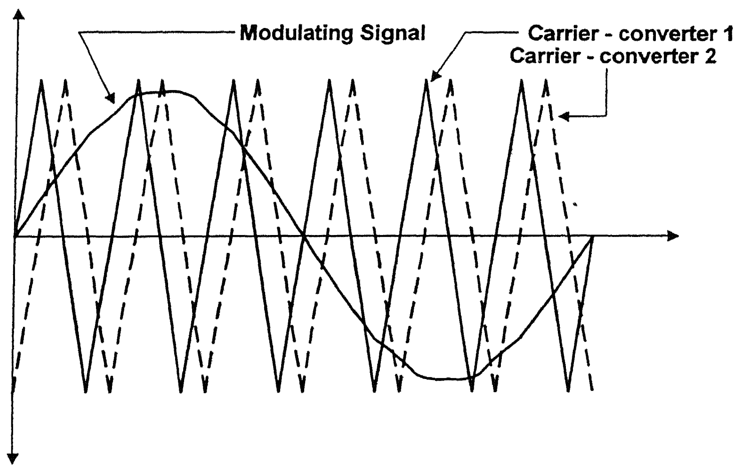


Fig. 4.4 Carrier Signals of Two Stage Converter

The power involved in traction system is very high. Due to use of single phase at high power, a large voltage drop and higher transmission losses are expected in the over head catenary supply. So it becomes necessary to maintain near unity power factor as low power factor has several ill effects like over loading of equipment in the traction substation. Harmonics in the catenary supply has undesirable effects such as the excitation of system resonance, decrease in the efficiency due to increased losses due to harmonics current, saturation and non linear behaviour of traction transformer, faulty operation of the signals and the interference with telecommunication lines which usually run by the side of track. With these considerations harmonic injection of single stage and two stage converters are analyzed. The power rating of the converter for a dense crush

loaded train of 800 tonnes will be approximately 1120 kW. The following data are used in simulation of single stage and two stage converters.

1. Traction power output = 1120 kW.
2. Transformer primary voltage = 22500 V.
3. Transformer secondary voltage = 680.0 V.
4. DC link voltage = 1500 V.
5. Synchronous link inductance = 0.7 mH.

Considering GTO thyristors based converters the optimal switching frequency for reliable operation with lesser switching losses at this power level is around 450 Hz [9][10]. The simulation results for single and two stage topologies for 450 Hz were presented in next section. To get conservative results, some assumptions were made in simulation. The supply voltage is assumed to be sinusoidal with no harmonics. All the semiconductor switches are assumed to be ideal. The inverter load is modeled as constant power load.

4.5 Simulation results at 450 Hz switching frequency

Fig. 4.5 to Fig. 4.10 show the simulation results for single and two stage topologies. In two stage converter the converters are effectively connected in series, on the primary side of traction transformer by virtue of the common step down transformer and so the equivalent voltage as seen from the primary side of transformer is sum of two input voltage of two converters as shown in Fig. 4.9. Fig. 4.7 shows that the dominant harmonics of single stage topology appear around 900 Hz, i.e., around $2f_c$ where f_c is the switching frequency. Fig. 4.10 shows the harmonic spectrum for two stage converter. Here the dominant frequencies appear at frequency around 1800 Hz (i.e., at $4f_c$). This is

due to fact that the carrier signals of the converters in two stage topology are displaced by $\pi/2$ radians. This result in cancellation of some harmonics reflected on the primary side of transformer. The equivalent carrier frequency on the primary side of transformer will be $4f_c$ where f_c is triangular carrier frequency of each converter. This eliminates the low order harmonics in the converter input voltage waveform on the primary side of traction transformer, and in the supply current. Table 4.2 and Table 4.3 give the harmonic magnitudes of supply currents for both topologies.

Table 4.4 shows the disturbance characteristics of single stage and two stage converters topologies. It suggests that a two stage converter gives better performance than a single stage converter from consideration of the psophometric disturbance current and total harmonic distortion in supply current. But the enforce limits for higher order harmonics are not met satisfactorily by any of these topologies. As the dominant harmonics depend upon switching frequency, it implies that as switching frequency increases the dominant harmonics moves to higher frequencies which can be easily filtered. Also at a particular switching frequency the dominant harmonics may fall outside the frequency region of enforced limits. But increase in switching frequency result in higher switching losses. In case of GTO thyristors based converters the safe and reliable operation with low switching losses limits the switching frequency to 450 Hz. Considering IGBT based converters, they can be relatively operated at much higher frequencies reliably when compared to GTO thyristor based converters [9][11]. This is due to the fact that IGBT has lower turn on and turn off when compared to GTO. Considering these facts, simulation results for two stage converter topology at switching frequency of 750 Hz were presented in next section.

4.5.1 Single stage topology

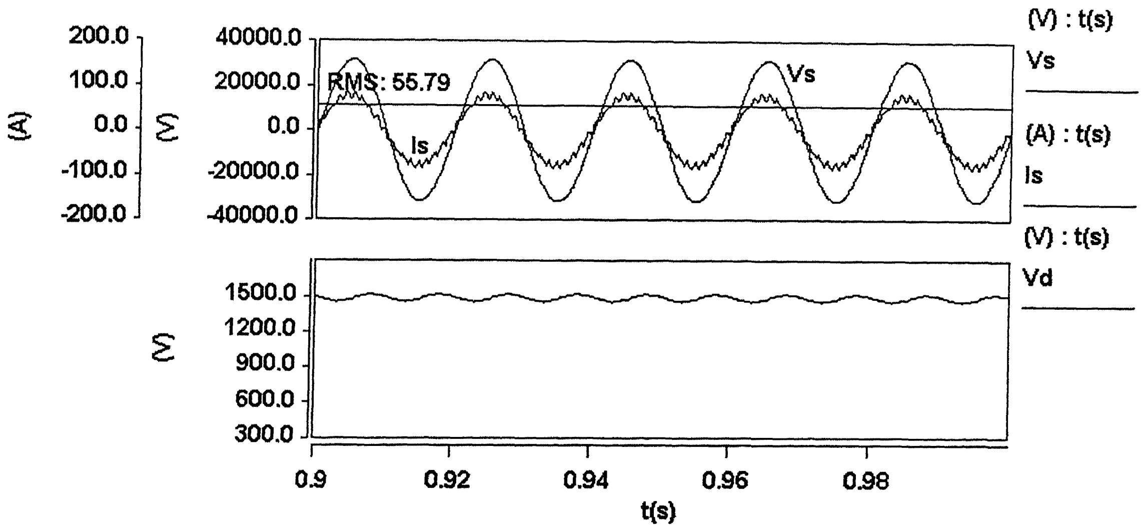


Fig. 4.5 Supply voltage, current and dc link voltage at steady state

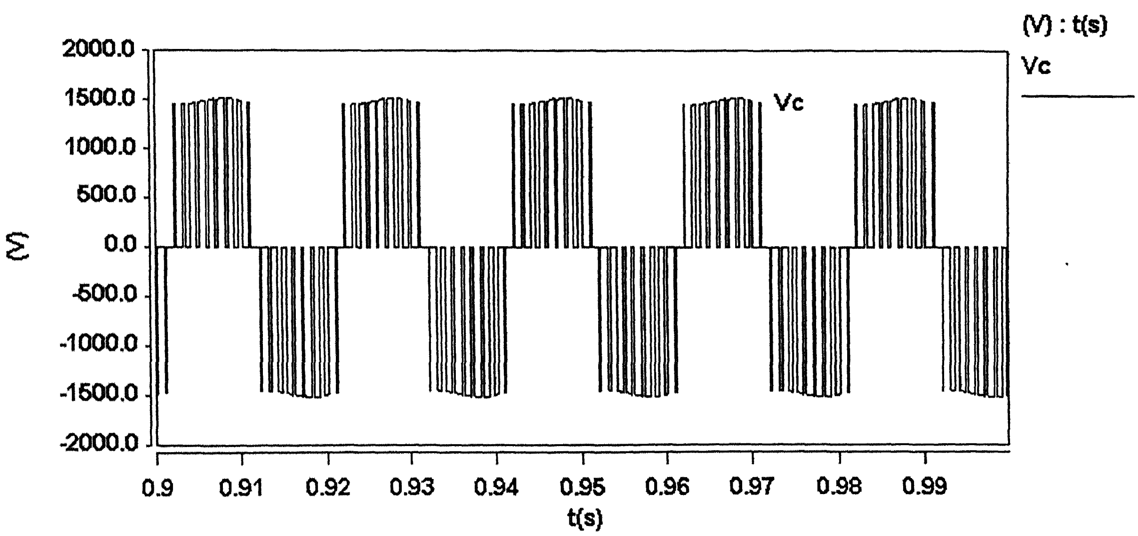


Fig. 4.6 Converter input voltage for single stage topology

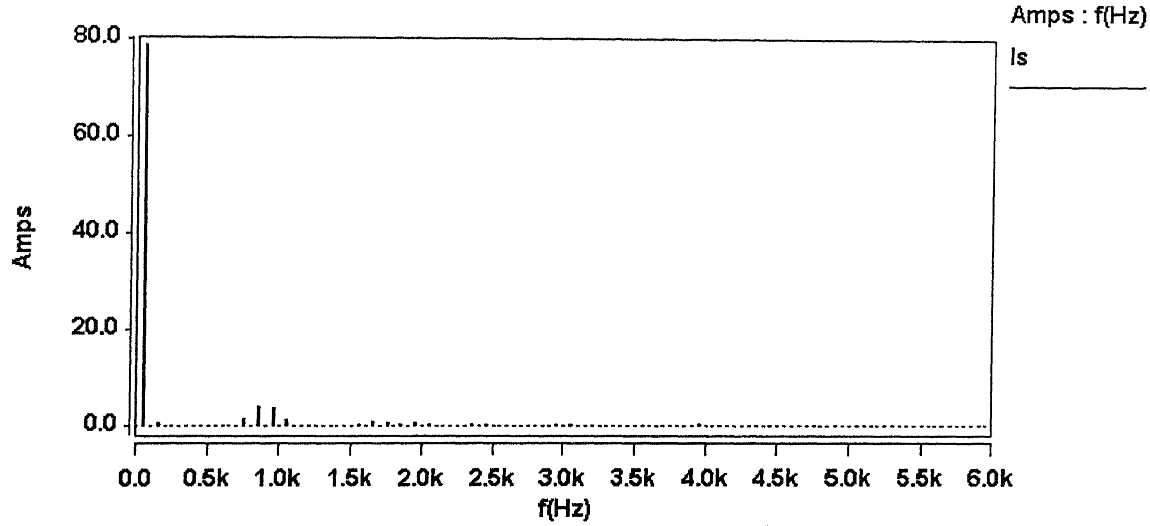


Fig. 4.7 Harmonic spectrum of supply current

4.5.2 Two stage topology

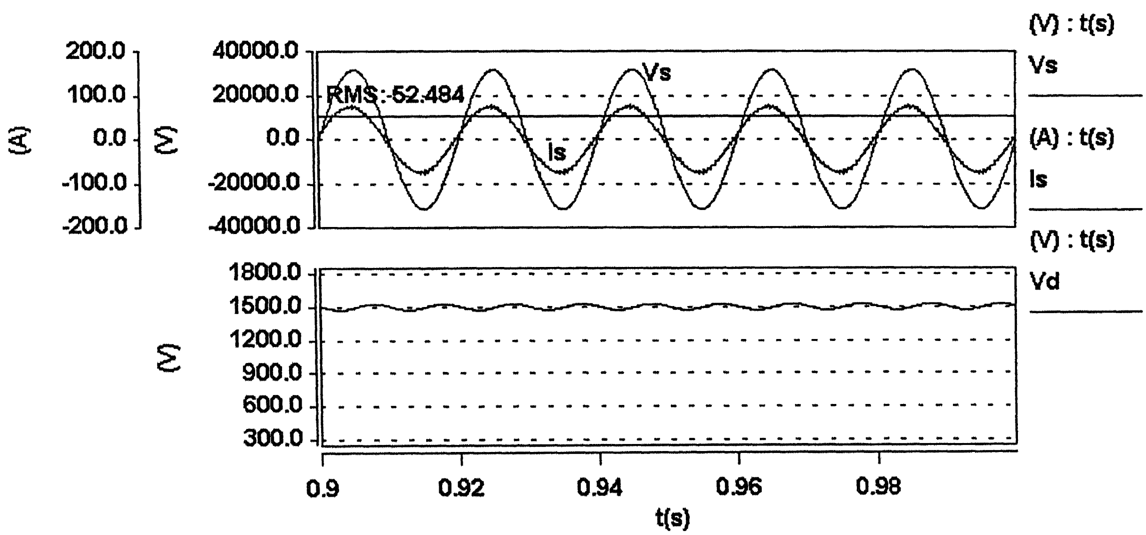


Fig. 4.8 Supply voltage current and dc link voltage at steady state

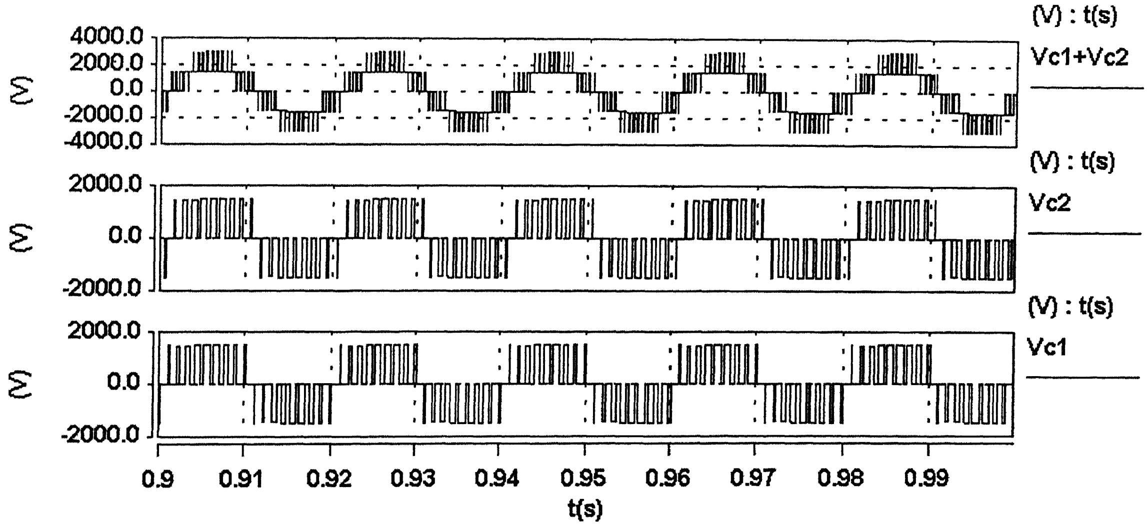


Fig. 4.9 Converter input voltages for two stage topology

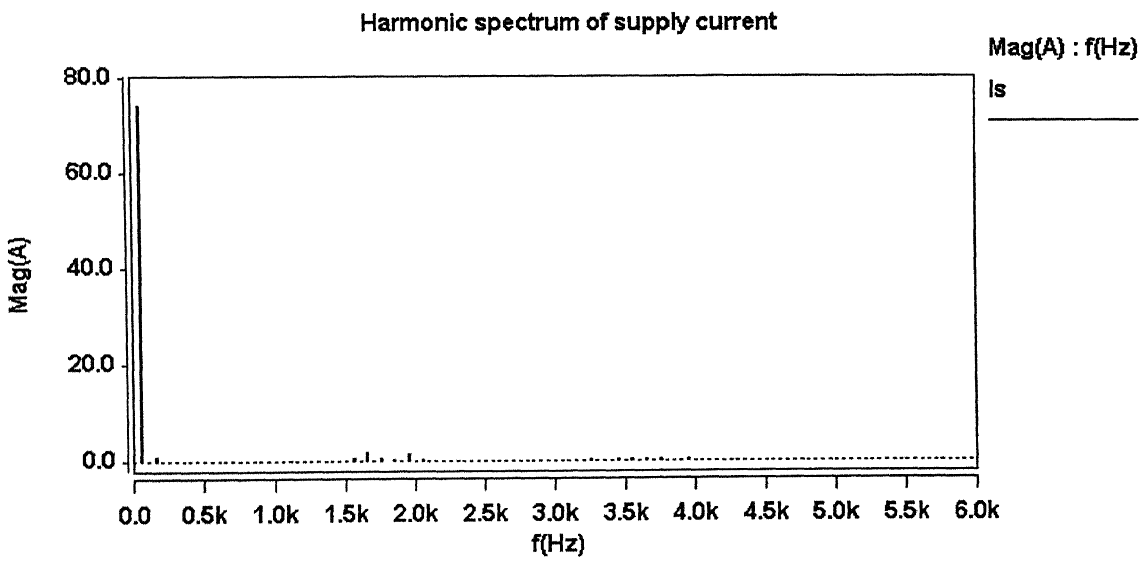


Fig. 4.10 Harmonic spectrum of supply current

Table 4.2 Harmonic magnitudes of single stage topology at 450 Hz

Frequency (Hz)	Magnitude (Amps)	Frequency (Hz)	Magnitude (Amps)	Frequency (Hz)	Magnitude (Amps)
0	0.03178	2k	157.2u	4k	68.95u
50	78.56	2.05k	0.3208	4.05k	0.1651
100	0.005241	2.1k	205.5u	4.1k	42.98u
150	0.4825	2.15k	0.05846	4.15k	0.008322
200	0.001244	2.2k	60.11u	4.2k	47.33u
250	0.01613	2.25k	0.06164	4.25k	0.0491
300	0.001174	2.3k	187.7u	4.3k	59.81u
350	0.01355	2.35k	0.2163	4.35k	0.06497
400	0.001068	2.4k	80.77u	4.4k	19.34u
450	0.006054	2.45k	0.3119	4.45k	0.0555
500	336.6u	2.5k	158.9u	4.5k	66.21u
550	0.01114	2.55k	0.1414	4.55k	0.05363
600	787.4u	2.6k	138.4u	4.6k	17.91u
650	0.1213	2.65k	0.02315	4.65k	0.09664
700	256.8u	2.7k	60.21u	4.7k	42.26u
750	1.555	2.75k	0.005428	4.75k	0.03933
800	684.7u	2.8k	137.4u	4.8k	56.67u
850	4.073	2.85k	0.119	4.85k	0.04096
900	346.8u	2.9k	32.94u	4.9k	36.16u
950	3.664	2.95k	0.2592	4.95k	0.04528
1k	23.81u	3k	154.6u	5k	20.88u
1.05k	1.115	3.05k	0.1927	5.05k	0.01644
1.1k	437.1u	3.1k	88.95u	5.1k	34.8u
1.15k	0.06767	3.15k	0.1673	5.15k	0.07473
1.2k	112.7u	3.2k	39.95u	5.2k	42.05u
1.25k	0.005989	3.25k	0.1568	5.25k	0.02298
1.3k	314.3u	3.3k	125.7u	5.3k	40.39u
1.35k	0.01093	3.35k	0.06065	5.35k	0.02637
1.4k	216.4u	3.4k	38.42u	5.4k	26.63u
1.45k	0.08183	3.45k	0.05486	5.45k	0.04703
1.5k	178.6u	3.5k	95.58u	5.5k	28.38u
1.55k	0.4396	3.55k	0.08232	5.55k	0.01743
1.6k	308.2u	3.6k	58.19u	5.6k	46.37u
1.65k	0.8085	3.65k	0.08236	5.65k	0.08266
1.7k	70.94u	3.7k	63.87u	5.7k	5.909u
1.75k	0.4957	3.75k	0.03395	5.75k	0.0282
1.8k	256.7u	3.8k	56.6u	5.8k	42.98u
1.85k	0.4633	3.85k	0.01197	5.85k	0.03032
1.9k	177.1u	3.9k	35.38u	5.9k	19.39u
1.95k	0.6845	3.95k	0.2056	5.95k	0.05945

Table 4.3 Harmonic magnitudes of two stage topology at 450 Hz

Frequency (Hz)	Magnitude (Amps)	Frequency (Hz)	Magnitude (Amps)	Frequency (Hz)	Magnitude (Amps)
0	0.03178	2k	157.2u	4k	68.95u
50	78.56	2.05k	0.3208	4.05k	0.1651
100	0.005241	2.1k	205.5u	4.1k	42.98u
150	0.4825	2.15k	0.05846	4.15k	0.008322
200	0.001244	2.2k	60.11u	4.2k	47.33u
250	0.01613	2.25k	0.06164	4.25k	0.0491
300	0.001174	2.3k	187.7u	4.3k	59.81u
350	0.01355	2.35k	0.2163	4.35k	0.06497
400	0.001068	2.4k	80.77u	4.4k	19.34u
450	0.006054	2.45k	0.3119	4.45k	0.0555
500	336.6u	2.5k	158.9u	4.5k	66.21u
550	0.01114	2.55k	0.1414	4.55k	0.05363
600	787.4u	2.6k	138.4u	4.6k	17.91u
650	0.1213	2.65k	0.02315	4.65k	0.09664
700	256.8u	2.7k	60.21u	4.7k	42.26u
750	1.555	2.75k	0.005428	4.75k	0.03933
800	684.7u	2.8k	137.4u	4.8k	56.67u
850	4.073	2.85k	0.119	4.85k	0.04096
900	346.8u	2.9k	32.94u	4.9k	36.16u
950	3.664	2.95k	0.2592	4.95k	0.04528
1k	23.81u	3k	154.6u	5k	20.88u
1.05k	1.115	3.05k	0.1927	5.05k	0.01644
1.1k	437.1u	3.1k	88.95u	5.1k	34.8u
1.15k	0.06767	3.15k	0.1673	5.15k	0.07473
1.2k	112.7u	3.2k	39.95u	5.2k	42.05u
1.25k	0.005989	3.25k	0.1568	5.25k	0.02298
1.3k	314.3u	3.3k	125.7u	5.3k	40.39u
1.35k	0.01093	3.35k	0.06065	5.35k	0.02637
1.4k	216.4u	3.4k	38.42u	5.4k	26.63u
1.45k	0.08183	3.45k	0.05486	5.45k	0.04703
1.5k	178.6u	3.5k	95.58u	5.5k	28.38u
1.55k	0.4396	3.55k	0.08232	5.55k	0.01743
1.6k	308.2u	3.6k	58.19u	5.6k	46.37u
1.65k	0.8085	3.65k	0.08236	5.65k	0.08266
1.7k	70.94u	3.7k	63.87u	5.7k	5.909u
1.75k	0.4957	3.75k	0.03395	5.75k	0.0282
1.8k	256.7u	3.8k	56.6u	5.8k	42.98u
1.85k	0.4633	3.85k	0.01197	5.85k	0.03032
1.9k	177.1u	3.9k	35.38u	5.9k	19.39u
1.95k	0.6845	3.95k	0.2056	5.95k	0.05945

Table 4.4 Disturbance characteristics of single stage and two stage converters at 450 Hz switching frequency

Particular	Enforced Limits	Single stage converter	Two stage converter
Psophometric current	≤ 10.0 A	6.3 A	1.91
DC Component of current	≤ 4.7 A	0.032	0.013
Second harmonic component	≤ 8.7 A	0.005	0.001
Audio frequency component			
1650 Hz	≤ 400.0 mA ampl.	808.5 mA	1722.0 mA
1750 Hz	≤ 400.0 mA ampl.	495.7 mA	473.4 mA
1950 Hz	≤ 400.0 mA ampl.	684.5 mA	1453.0 mA
2050 Hz	≤ 400.0 mA ampl.	320.8 mA	470.5 mA
2250 Hz	≤ 400.0 mA ampl.	61.6 mA	9.4 mA
2350 Hz	≤ 400.0 mA ampl.	216.3 mA	3.1 mA
2550 Hz	≤ 400.0 mA ampl.	141.4 mA	18.6 mA
2650 Hz	≤ 400.0 mA ampl.	23.2 mA	17.52 mA
High frequency component			
5050 Hz	≤ 270.0 mA ampl.	16.4 mA	85.3 mA
5100 Hz	≤ 270.0 mA ampl.	0.0 mA	0.0 mA
THD of input current		7.67 %	3.63 %

4.6 Simulation results for two stage topology at 750 Hz

Fig 4.11 to 4.13 and Table 4.5 & 4.6 shows the simulation results and the harmonic disturbance characteristics of two stage converter at 750 Hz. The results show that at this frequency the performance of two stage converter is satisfactory in consideration with all the enforced limits listed in Table 4.1. This system will suits well for medium power application in traction.

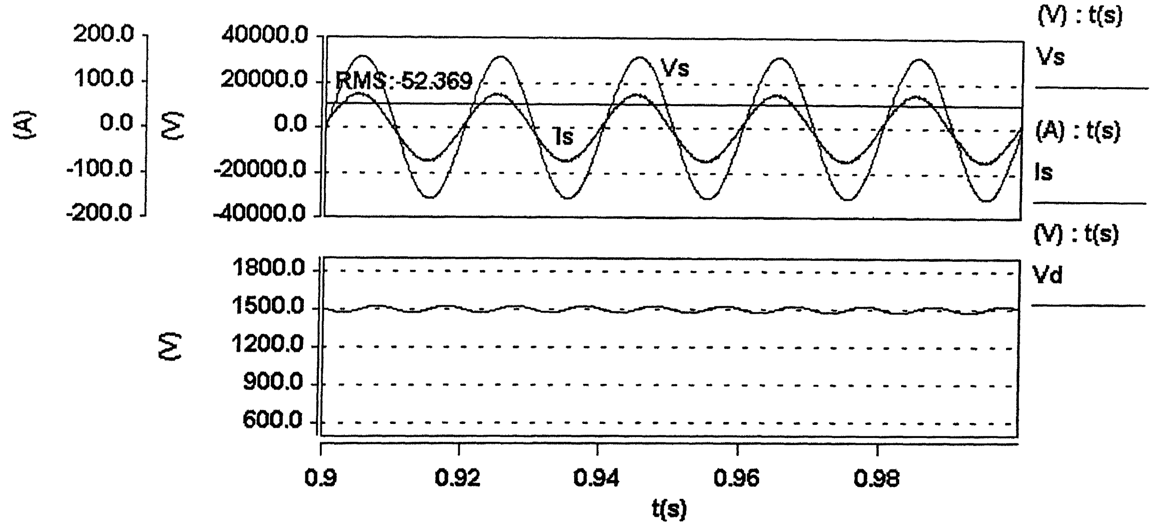


Fig. 4.11 DC-Link voltage, supply current and supply voltage during steady state for two stage topology at 750 Hz

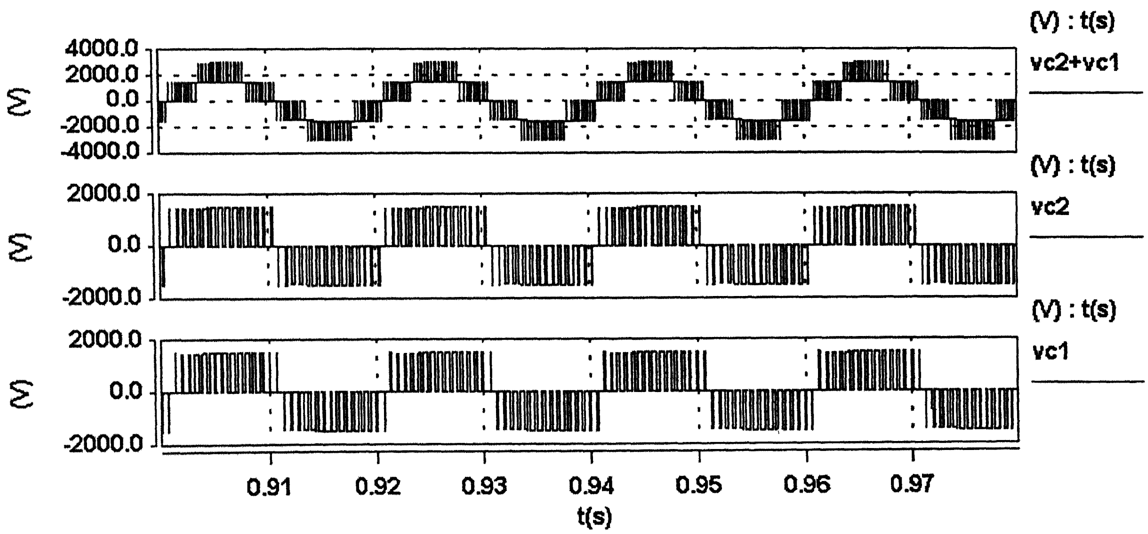


Fig. 4.12 Input voltages of converters

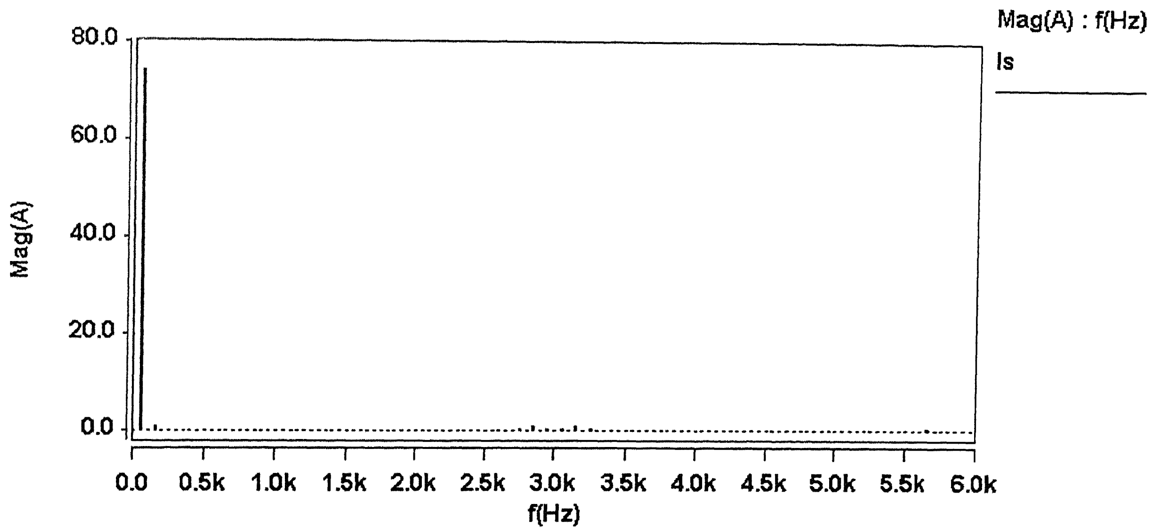


Fig. 4.13 Harmonic spectrum of supply current

Table 4.5 Disturbance characteristics of two stage converter topology operating at switching frequency of 750 Hz

Particular	Enforced Limits	Two stage converter
Psophometric current	≤ 10.0 A	0.6135
DC Component of current	≤ 4.7 A	0.013
Second harmonic component	≤ 8.7 A	0.0032
Audio frequency component 1650 Hz 1750 Hz 1950 Hz 2050 Hz 2250 Hz 2350 Hz 2550 Hz 2650 Hz	 ≤ 400.0 mA ampl. ≤ 400.0 mA ampl. ≤ 400.0 mA ampl. ≤ 400.0 mA ampl. ≤ 400.0 mA ampl. ≤ 400.0 mA ampl. ≤ 400.0 mA ampl. ≤ 400.0 mA ampl.	 22.16 mA 10.38 mA 15.89 mA 17.88 mA 12.69 mA 15.52 mA 15.69 mA 41.14 mA
High frequency component 5050 Hz 5100 Hz	≤ 270.0 mA ampl. ≤ 270.0 mA ampl.	13.78 mA 0.00 mA
THD of input current		2.353 %

Table 4.6 Harmonic magnitudes of two stage converter topology at 750 Hz

Frequency (Hz)	Magnitude (Amps)	Frequency (Hz)	Magnitude (Amps)	Frequency (Hz)	Magnitude (Amps)
0	0.03178	2k	157.2u	4k	68.95u
50	78.56	2.05k	0.3208	4.05k	0.1651
100	0.005241	2.1k	205.5u	4.1k	42.98u
150	0.4825	2.15k	0.05846	4.15k	0.008322
200	0.001244	2.2k	60.11u	4.2k	47.33u
250	0.01613	2.25k	0.06164	4.25k	0.0491
300	0.001174	2.3k	187.7u	4.3k	59.81u
350	0.01355	2.35k	0.2163	4.35k	0.06497
400	0.001068	2.4k	80.77u	4.4k	19.34u
450	0.006054	2.45k	0.3119	4.45k	0.0555
500	336.6u	2.5k	158.9u	4.5k	66.21u
550	0.01114	2.55k	0.1414	4.55k	0.05363
600	787.4u	2.6k	138.4u	4.6k	17.91u
650	0.1213	2.65k	0.02315	4.65k	0.09664
700	256.8u	2.7k	60.21u	4.7k	42.26u
750	1.555	2.75k	0.005428	4.75k	0.03933
800	684.7u	2.8k	137.4u	4.8k	56.67u
850	4.073	2.85k	0.119	4.85k	0.04096
900	346.8u	2.9k	32.94u	4.9k	36.16u
950	3.664	2.95k	0.2592	4.95k	0.04528
1k	23.81u	3k	154.6u	5k	20.88u
1.05k	1.115	3.05k	0.1927	5.05k	0.01644
1.1k	437.1u	3.1k	88.95u	5.1k	34.8u
1.15k	0.06767	3.15k	0.1673	5.15k	0.07473
1.2k	112.7u	3.2k	39.95u	5.2k	42.05u
1.25k	0.005989	3.25k	0.1568	5.25k	0.02298
1.3k	314.3u	3.3k	125.7u	5.3k	40.39u
1.35k	0.01093	3.35k	0.06065	5.35k	0.02637
1.4k	216.4u	3.4k	38.42u	5.4k	26.63u
1.45k	0.08183	3.45k	0.05486	5.45k	0.04703
1.5k	178.6u	3.5k	95.58u	5.5k	28.38u
1.55k	0.4396	3.55k	0.08232	5.55k	0.01743
1.6k	308.2u	3.6k	58.19u	5.6k	46.37u
1.65k	0.8085	3.65k	0.08236	5.65k	0.08266
1.7k	70.94u	3.7k	63.87u	5.7k	5.909u
1.75k	0.4957	3.75k	0.03395	5.75k	0.0282
1.8k	256.7u	3.8k	56.6u	5.8k	42.98u
1.85k	0.4633	3.85k	0.01197	5.85k	0.03032
1.9k	177.1u	3.9k	35.38u	5.9k	19.39u
1.95k	0.6845	3.95k	0.2056	5.95k	0.05945

4.7 Modified Two Stage Topology

In this topology, one converter of two stages will be main converter providing the necessary fundamental power required by load. The other converter is made to operate as active power filter which supplies the harmonic power required by the main converter. Here the main converter operates at low switching frequency 450 Hz and the converter is designed to handle high fundamental power. On the other hand the auxiliary converter is designed for low power rating used to compensate for harmonic currents. This converter operates in hysterisis current control mode [12]. Fig. 4.14 to 4.16 and Table 4.7 & 4.8 give the simulation results and disturbance characteristics of modified two stage topology.

The simulation results suggest that the performance of this topology is satisfactory when compared with single stage topology in consideration with the enforced limits. The harmonic magnitudes can be reduced to desired level by changing the hysteresis band of the reference input current. The results show that main converter supplies the required fundamental power while the auxiliary converter essentially supplies the harmonic power required for main converter. The rms current magnitude flowing through auxiliary converter is around 13 % of that main converter. This means that the rating of auxiliary converter is around 15 % of the main converter rating. This result in cost saving when compared to two stage converter topology with fixed frequencies. Since the high frequency switching of auxiliary converter is done at lower power level there will not much difference in switching losses of two stage topology and this topology. Further in this the main converter operates at a lower frequency of 450 Hz which results in lower losses.

Table 4.7 Harmonic magnitudes of modified two stage converter

Frequency (Hz)	Magnitude (Amps)	Frequency (Hz)	Magnitude (Amps)	Frequency (Hz)	Magnitude (Amps)
0	0.0312	2k	0.0506	4k	0.07664
50	79.56	2.05k	0.1056	4.05k	0.1843
100	0.1576	2.1k	0.04957	4.1k	0.06035
150	1.413	2.15k	0.1411	4.15k	0.1381
200	0.1703	2.2k	0.03103	4.2k	0.019
250	0.2501	2.25k	0.0836	4.25k	0.07461
300	0.1203	2.3k	0.01518	4.3k	0.05311
350	0.09812	2.35k	0.1661	4.35k	0.1563
400	0.1459	2.4k	0.01421	4.4k	0.06343
450	0.1207	2.45k	0.1088	4.45k	0.1084
500	0.2353	2.5k	0.05354	4.5k	0.0273
550	0.0843	2.55k	0.1016	4.55k	0.0832
600	0.2237	2.6k	0.06236	4.6k	0.04148
650	0.1217	2.65k	0.08815	4.65k	0.2074
700	0.1225	2.7k	0.02923	4.7k	0.07551
750	0.4485	2.75k	0.09575	4.75k	0.09162
800	0.0404	2.8k	0.05045	4.8k	0.0662
850	0.7934	2.85k	0.2436	4.85k	0.04139
900	0.04608	2.9k	0.05422	4.9k	0.03944
950	0.8793	2.95k	0.02401	4.95k	0.04656
1k	0.06541	3k	0.04954	5k	0.03369
1.05k	0.3782	3.05k	0.08167	5.05k	0.1183
1.1k	0.07935	3.1k	0.0354	5.1k	0.02329
1.15k	0.2053	3.15k	0.02463	5.15k	0.07255
1.2k	0.1207	3.2k	0.01811	5.2k	0.01232
1.25k	0.1821	3.25k	0.1549	5.25k	0.08191
1.3k	0.08373	3.3k	0.0584	5.3k	0.06739
1.35k	0.2636	3.35k	0.09883	5.35k	0.08417
1.4k	0.05724	3.4k	0.08532	5.4k	0.05854
1.45k	0.1472	3.45k	0.1264	5.45k	787.5u
1.5k	0.07985	3.5k	0.07187	5.5k	0.009726
1.55k	0.2431	3.55k	0.05739	5.55k	0.06569
1.6k	0.08246	3.6k	0.04854	5.6k	0.04885
1.65k	0.2108	3.65k	0.1563	5.65k	0.1298
1.7k	0.07057	3.7k	0.01449	5.7k	0.08685
1.75k	0.3608	3.75k	0.09968	5.75k	0.05676
1.8k	0.05385	3.8k	0.0382	5.8k	0.08067
1.85k	0.3725	3.85k	0.006262	5.85k	0.06987
1.9k	0.04573	3.9k	0.05193	5.9k	0.04059
1.95k	0.4473	3.95k	0.1989	5.95k	0.1417

Table 4.8 Disturbance characteristics of modified two stage topology

Particular	Enforced Limits	Modified Two stage converter
Psophometric current	≤ 10.0 A	1.6419
DC Component of current	$\leq$ 4.7 A	0.0312
Second harmonic component	≤ 8.7 A	0.1576
Audio frequency component		
1650 Hz	≤ 400.0 mA ampl.	210.8 mA
1750 Hz	≤ 400.0 mA ampl.	360.8 mA
1950 Hz	≤ 400.0 mA ampl.	447.3 mA
2050 Hz	≤ 400.0 mA ampl.	105.6 mA
2250 Hz	≤ 400.0 mA ampl.	83.60 mA
2350 Hz	≤ 400.0 mA ampl.	166.1 mA
2550 Hz	≤ 400.0 mA ampl.	101.6 mA
2650 Hz	≤ 400.0 mA ampl.	88.15 mA
High frequency component		
5050 Hz	≤ 270.0 mA ampl.	118.3 mA
5100 Hz	≤ 270.0 mA ampl.	23.29 mA
THD of supply input current		2.96 %
THD of main converter input current		7.72 %
THD of auxi. converter input current		67 %

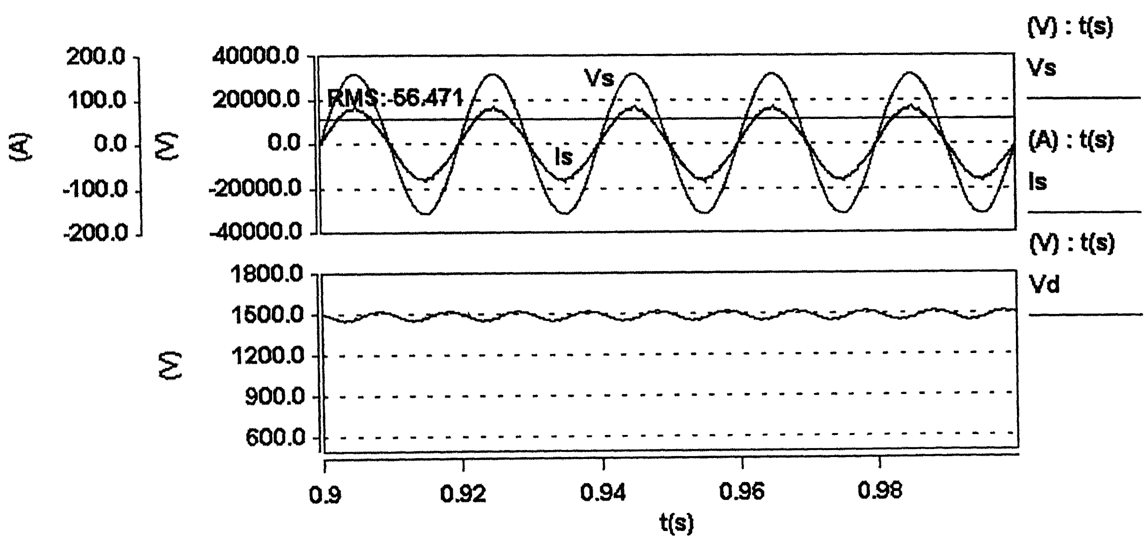


Fig. 4.14 Supply current voltage and dc link voltage waveforms at steady state

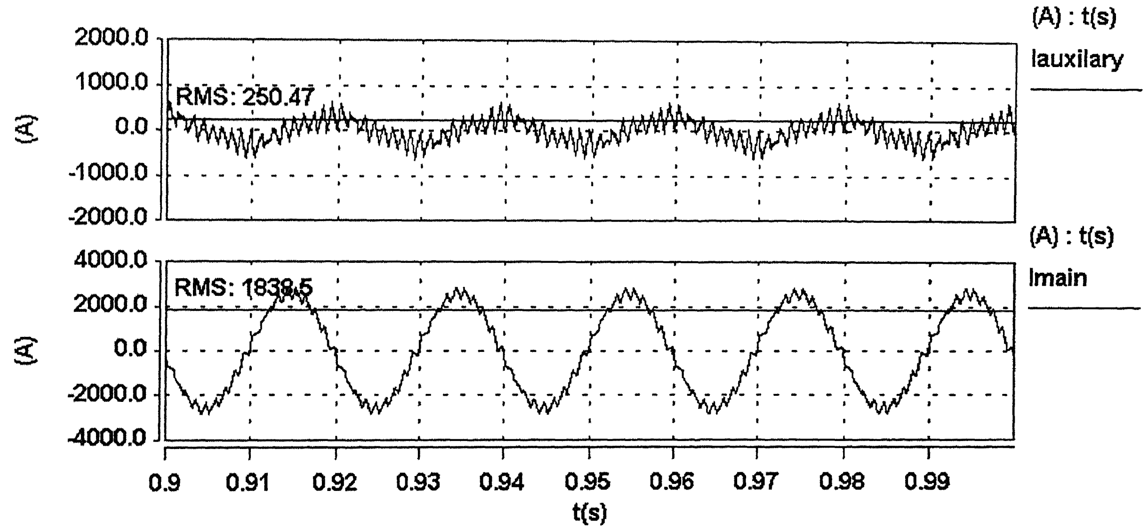


Fig. 4.15 Input current wave forms of main and auxiliary converter

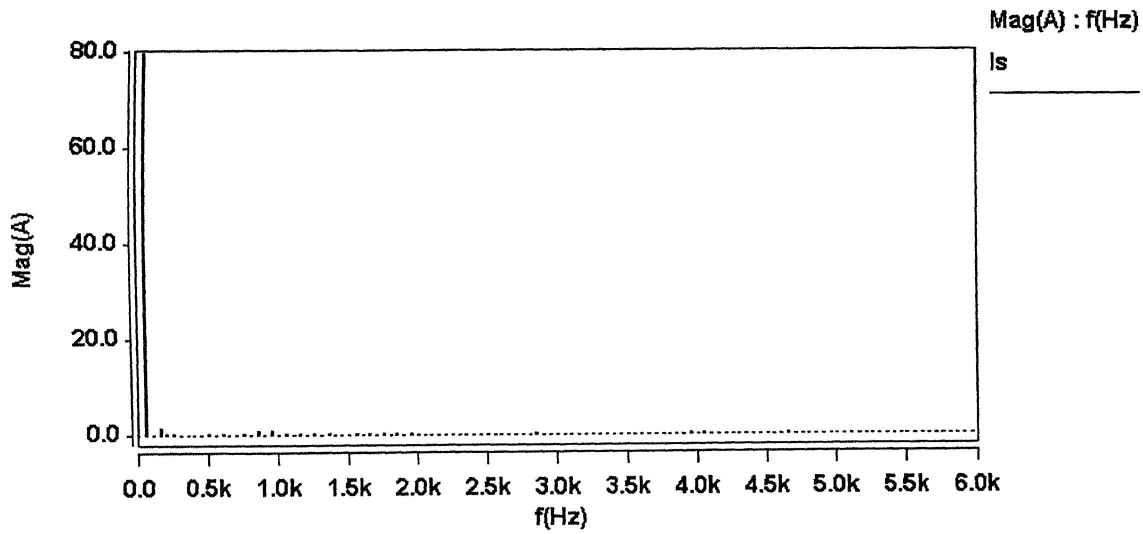


Fig. 4.16 Harmonic spectrum of supply current

In the preceding sections, application of synchronous link converter to a 25 kV ac traction systems was presented for forward power flow condition. The characteristics will remain same for reverse power flow condition (during regeneration) This is due to fact that harmonic voltages and harmonic currents at the converter input terminals are function of modulation index and is independent of the phase of converter input voltage

with respect to the supply voltage. During reverse power flow the phase of converter input voltage is made to lead the supply voltage, and the modulation index remains almost constant (assuming the power level to be the same). Hence the psophometric current characteristics remain same for either directions of the power flow.

4.8 Advantages of Synchronous Link Converter as a Front-end Converter in Modern Electric Traction Systems

The applications of Synchronous Link Converter in a 25 kV ac traction systems may result in the following advantages:

1. Usage of Synchronous Link Converter as front-end converter result in good performance from consideration of psophometric current, dc component, audio frequency component and high frequency components currents in the over head catenary, so practically there is no interference with the track and the telecommunication equipments.
2. Due to operation of the Synchronous Link Converter at near unity power factor, under forward and reverse power flow conditions, there is a reduction in the losses in over head catenary supply. This results in the economic operation of traction substations.
3. There is an increase in the life and a reduction in the maintenance of brake equipments, brake blocks, wheel tyres and control equipments, owing to the availability of regenerative braking from the maximum speed up to near standstill condition

4. Utilization of traction transformer leakage inductance as synchronous link converter and results in the reduction in volume, weight, losses etc. associated with an independent synchronous link inductor.
5. The Synchronous Link Converter can be designed to operate with large variations in catenary voltage.
6. There is no need for Var Compensator at the input terminals.
7. There is no need for low frequency harmonic filters at the input terminals.

Due to the above mentioned advantages, Synchronous Link Converter can be used as a front-end converter in a Modern 25 kV Regenerative AC Traction Drive Systems.

Chapter 5

Conclusion and Scope for future work

Using Synchronous Link Converter as front-end converter for traction system gives better performance by minimizing harmonic injection into overhead catenary supply and thus prevents from undesirable effects such as excitation of system resonance, faulty operation of signals and interference with telecommunication lines which usually run by the side of track. Due to the use of PWM switching in converter system, the dominant harmonics appear at well defined frequencies. The dominant harmonic frequencies in order of the amplitude are around $2f_c \pm f_s$, for single stage topology and $4f_c \pm f_s$, for two stage topology. Passive filters can be designed to suppress these harmonics from entering into the supply.

By proper design of converter, the system can be operated satisfactorily even with wide variations in catenary voltage. When there is decrease in catenary voltage the input currents to Synchronous Link Converter increases at unity power factor until it reaches "cut off current limit". This limit depends upon rms current rating of the switching devices used. Beyond this limit, the input current is maintained constant and hence there will be reduction in power input to converter and the system is operated with unity power factor at reduced power output.

Hence the synchronous link converter meets the requirements of the front-end converters for Electric Traction systems. In this thesis, digital simulations of both single and dual converter topologies are carried out using SABER simulator and the

performance of the systems are analyzed. Unity power factor condition is maintained at the input in both the cases. Experimental investigation is carried out for single converter topology and typical experimental results are compared with simulation results with good agreement.

5.1 Scope for Future Work

The present simulations were made by modeling the inverter load a constant current load. The work can be extended to study the psophometric disturbance current analysis by loading the dc link capacitor with a PWM inverter motor drive. The analysis input current harmonics of front-end converter system can be done with modern drive systems employing DTC technique on other side of dc link.

Further, in these simulations the switches were assumed to be ideal. Work can be extended by designing the converter system based on ratings of available power semiconductor switches by taking into consideration of their switching losses, lockout period during PWM control.

Appendix-A

Information related to Psophometric current Evaluation

Harmonic Number	Weightage Factor	Harmonic number	Weightage Factor	Harmonic Number	Weightage Factor
1	0.0007	21	1.109	41	0.698
2	0.009	22	1.072	42	0.689
3	0.035	23	1.035	43	0.679
4	0.089	24	1	44	0.67
5	0.178	25	0.977	45	0.661
6	0.295	26	0.955	46	0.652
7	0.376	27	0.928	47	0.643
8	0.484	28	0.905	48	0.634
9	0.582	29	0.881	49	0.625
10	0.661	30	0.861	50	0.617
11	0.733	31	0.842	51	0.607
12	0.794	32	0.824	52	0.598
13	0.851	33	0.807	53	0.59
14	0.902	34	0.791	54	0.58
15	0.955	35	0.775	55	0.571
16	1	36	0.76	56	0.562
17	1.035	37	0.745	57	0.553
18	1.072	38	0.732	58	0.543
19	1.109	39	0.72	59	0.525
20	1.122	40	0.708	60	0.525

Appendix-B

Specifications of PCL – 208 Data Acquisition card

PCL – 208 is a high performance, high speed, multifunction data acquisition card for the IBM PC/XT/AT or compatibles. The high end specifications of this full size card and complete software support make it ideal for wide range of applications in the industrial and laboratory environment, like data acquisition, process control, automatic testing and factory automation.

Main features:

- Switch selectable 16 single – ended or 8 differential analog input channels.
- An industrial standard 12 Bit successive approximation converter (ADC674) to convert analog inputs. The maximum A/D sampling rate is 60 kHz in DMA mode.
- Switch selectable versatile analog input ranges.

  Bipolar: +/- 0.5 V, +/- 1 V, +/- 2.5 V, +/- 5 V, +/- 10 V.

  Unipolar: +1V, +2V, +5V, +10V.
- Provides three A/D trigger modes: software trigger, Programmable pacer t rigger and external trigger pulse trigger.
- A/D converted data can be transferred by program control, interrupt handler routine or DMA transfer.
- An INTEL 8254 Programmable Timer/ Counter provides pacer output (trigger pulse) at the rate of 2.5 MHz to 71 minutes / pulse to the A/D. The timer time

base is switch selectable 10 MHz or 1 MHz. One 16 – bit counter channel is reserved for user configuration applications.

- Two 12 bit monolithic multiplying D/A output channels. Output range of 0 to +5V can be created by using the onboard -5 V reference. This precision reference is derived from the A/D converter reference. External AC or DC reference can also be used to generate other D/A output ranges.
- TTL/DTL compatible 16 digital input & 16 digital output channels.

A/D & D/A converter Specifications

Analog Input Specifications:

Channels	:	16 Single-ended or 8 Differential, switch selectable.
Resolution	:	12 bits.
Input Range	:	Unipolar: +1V, +2V, +5V, +10V.
		Bipolar: +/- 0.5 V, +/- 1 V, +/- 2.5 V, +/- 5 V, +/- 10 V.
		All input ranges are switch selectable.
Over voltage	:	Continuous +/- 30 V Max.
Conversion Type	:	Successive Approximation.
Conversion Speed	:	60 kHz max.
Accuracy speed	:	0.01% of reading +/- 1 bit.
Linearity	:	+/- 1 bit.
Trigger Mode	:	Software trigger, onboard programmable timer or external trigger.
Data transfer	:	Program control, Interrupt control or DMA.

Analog Output Specifications:

Channels	:	2 channels.
Resolution	:	12 bits.
Output Range	:	0 to +5V with fixed -5V reference.
		+/- 10 V with external DC or AC reference.
Reference Voltage	:	Internal: -5V (+/- 0.05V).
		External: DC or AC, +/- 10V max.
Conversion Type	:	12 bit monolithic multiplying (DAC 7541)
Linearity	:	+/- ½ bit.
Output Drive	:	+/- 5 mA max.
Settling Time	:	5 microseconds.

General Specifications:

Power Consumption	:	+5 V	:	typ. 700 mA, max. 1A.
		+12 V	:	typ. 140 mA, max. 200mA.
		-12 V	:	typ. 14mA, max. 20mA.
I/O Connector	:	20 pin flat cable connector for all Analog/Digital I/O ports.		
I/O Base Address	:	Requires 16 consecutive address locations. Base address is definable by the DIP switches for address lines A9 – A4.		

Specifications used in Experimental work: 16 Single-ended Analog input channels, bipolar +/-10V, -5V internal reference.

Appendix-C

Real Time Program for closed loop control

```
/* Program used for closed loop control of Synchronous Link Converter */
#include<stdio.h>
#include<conio.h>
#include<time.h>
#include<dos.h>
#include<math.h>
#include BASE_ADDRESS ox300H
void main ()
{       float kp = 0.1, ki = 2.5, im, vl, vdc, vdc_ref = 100.0, err, er0, pi, Ls = 7.146;
        int check = 0, u = 0, val = 0, vl2 = 2047, hi = 159, lo = 240, lo1 = 0, muxscan,
        trigger, ch1, ch1, ch0;
        double T = 0.000002;
        while (1)
        {       muxscan = 0;
                trigger = 0;
                outportb (BASE_ADDRESS + 2,muxscan);
                outportb (BASE_ADDRESS + 0,trigger);
                while ( 1 )
                {       u = inportb (BASE_ADDRESS + 8);
                        check = u;
                        check & = 0x80;
                        if (!check)
                        break;
                }
                ch0 = inportb (BASE_ADDRESS+0);
                ch1 = ch0 >> 4;
                ch2 = inportb (BASE_ADDRESS+1);
```

```
            val = ((ch2&0xff) * 16 + ch1),
            vdc = (val-2047) * 200.0/2047;
            err = vdc_ref – vdc;
            if ((err < 0.1) && (err > -0.1))
            {       err = 0.0;
            }
            pi = pi + kp * (err – er0) + ki * err * T;
            er0 = err;
            im = pi;
            vl = im * Ls;
            if (vl > 38.0)
            {       vl = 38.0;
                    pi = 5.25;
            }
            if (vl < -38.0)
            {       vl = -38.0;
                    pi = -5.25;
            }
            vl2 = ((vl * 2047) / 38) + 2048;
            lo1 = vl2 % 16;
            lo = lo1 << 4;
            hi = vl2 / 16;
            outportb (BASE_ADDRESS + 4,lo);
            outportb (BASE_ADDRESS + 5,hi);
      }
}
```

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